AFIT/GEE/ENV/94S-19

SIMULATION OF HYDROLOGIC INFLUENCES ON WETLAND ECOSYSTEM SUCCESSION

THESIS

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THESIS

Presented to the Falculty of the School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the degree of

Master of Science in Engineering and Environmental Management

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August 1994

Preface

This research paper required a great deal of support from a number of individuals. Those deserving special recognition for their contributions included my thesis advisor, Lt Col Mike Shelley and my thesis reader, Maj J. Andreas Howell. Also, a special thanks goes to Dr. James Amon of Wright State University who provided valuable information as to the complexities and functions of wetlands. All three of these individuals provided invaluable guidance and insight throughout the entire research process. As the research was conducted, they allowed me a great deal of flexibility and latitude in developing the ideas and thought processes in the development of this study.

My greatest appreciation, however, goes to my family and especially my wife. They made many sacrifices throughout this reach effort and endured many a night when I was unavailable for them. Without my wife's support, help and never ending encouragement, I could not have successfully completed this research effort. For this, I give my them my undying respect and love. Thanks.

Robert A. Pompilio

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Abstract

This research focuses on the development of a simulation model to determine the affects of hydrological influences on a wetland ecosystem. The model allows perturbations to the inputs of various wetland data which in turn, influences the successional development of the ecosystem.

This research consisted of converting a grassland ecosystem model to one which simulates wetland conditions. The critical factor in determining the success of wetland creation is the hydrology of the system. There are four of the areas of the original model which are affected by the hydrology. They are; nutrients recycling , plant biomass development, species diversity, and organic decomposition. Thirty auxiliary variable constants influenced over ninety system parameters of the original model. To convert this to reflect that of a wetland, twenty two were changed and eight additional new auxiliary variables were added.

The model measures the health or success of the ecosystem through the measurement of the systems gross plant production, the respiration and the net primary production of biomass. Altering the auxiliary variables of water level and the rate of flow through the system explicitly details the affects hydrologic influences on those production rates. Ten case tests depicting exogenous perturbations of the hydrology were run to identify these affects. Although the tests dealt with the fluctuation of water through the system, any one of the auxiliary variables in the model could be changed to reflect site specific data. The results of those changes would then determine the viability of a successful wetland development. This allows environmental managers throughout the Air Force to apply the model towards the construction or mitigation of any type of wetland area.

Simulation of Hydrologic Influences on Wetland Ecosystem Succession

I. Background Information

Introduction

Wetlands are complex ecosystems providing habitats for hundreds of animal species, breeding grounds for hundreds more, temporary nesting for migratory fowl, erosion control of shorelines, ground water recharge centers and much more. Yet it was not until the late 1970's that this unique and fragile system was recognized as a valuable asset to society. Wetlands, a generic, all encompassing term, is now accepted as the means for describing virtually every type of shallow water environment. The wetlands are ubiquitous, that is to say they are a major feature on every continent except Antarctica and in every climate, tundra included (3:4). But for years, the value of the wetlands were never realized by our society. The impact of humans on the particular ecosystem is virtually impossible to estimate. In heavily populated and developed regions, destruction of wetlands ranged from significant to total (3:5). Many of our major airports and several large cities are situated entirely, or in part, on former wetlands (3:5). For centuries the vast majority of society viewed wetlands (swamps and bogs, etc.) as vast reservoirs for disease and unfit for farming or development (1:1). In fact, prior to the mid 1970's, certain government policies encouraged the practice of draining and destroying the wetlands for developmental reasons (3:15). Had these trends continued, our wetlands would now be an endangered ecosystem (3:15). Ironically, hunters and fisherman first saw a relationship between wetlands and the ecology. They noted the direct decline of populations of valuable shellfish, birds, reptiles, and fur-bearing animals which depended

on the wetlands, as they were destroyed (1:16). Indeed, up to the year 1987, it has been estimated that the rate of wetland loss was between 300,000 to 485,000 acres per year and of the original 215 million acres believed to have existed in the contiguous United States, only about 95 million remain (4:1).

In 1977, these trends slowly started to reverse. With increasing awareness of the economic value of wetlands, President Carter signed into law Executive Order 11990 - Protection of Wetlands. Permitting requirements and impact analysis were required for any expansion or development into wetland areas. Thirteen years later, President Bush expanded these permitting procedures by signing an executive order which called for a goal of no net loss of wetlands (2:2). It is this order which drives the current policy of the Air Force. Any type of design or construction project which affects a wetland area must provide for the mitigation of that area. Thus arises the need for identifying and categorizing our nation's wetland areas. Understanding the environmental ecosystems associated with each classification of wetland will help enable managers and designers to successfully create and enhance wetland areas for mitigation purposes.

General Problem Statement

With more and more focus on the preservation, restoration, mitigation and creation of wetland regions, accurate methods defining the parameters of creation or restoration need to be developed. Hydrology is extremely important in developing the structure and function of a wetland. It is this ingredient which creates unique physiochemical conditions that allow the formation of a vastly different ecosystem than those of well-drained terrestrial and deep water aquatic systems (3:68). The hydrology of the system is dependent on the regional climatic and topographic characteristics as well as local characteristics. The mass water flow of a wetland is an important factor in the

development of the soil, vegetation and wildlife diversity of the system. Bearing these factors in mind, the proper management and optimization of the productivity of the wetland is best characterized in a simulation model of the system. The modeling will better our understanding of how the system interacts and what to expect when we change or disturb it. It will enable us to see how a slight change in one parameter will affect the total wetland area and its downstream components (8:1). It is the general consensus of several international scientists that mathematical and conceptual modeling be utilized as an integral part of wetland ecology and management (21:1). It is rather obvious that modeling all the parameters of a wetland and their unique effects on the system is too large an undertaking for this paper. Therefore, this paper deals with a conceptual model limited only to wetland hydrology and its effects on the system. This approach is taken in recognition of the importance of hydrologic conditions in the delineation function and productivity of the wetlands.

Specific Problem Statement

What are the critical system parameters, with respect to hydrological inputs and their impact on subsequent successional changes to the ecosystem, associated with the creation and enhancement of inland freshwater wetlands? The critical factor in determining the success of wetland creation is the hydrology of the system. Maintaining an adequate water budget to allow the abiotic and biotic factors sufficient time to develop is paramount to this success. A mathematical model which characterizes the effects of hydrology on a wetland will employ the critical parameters which create this ecological system. Subsequent perturbations to the hydrologic inputs will display how the system reacts to change, witn respect to its net primary production. The causal diagram, figure 1-1, shows schematically terms how hydrology influences the soil characteristics which in

turn influence the vegetative growth. The model feeds back upon itself by way of the resulting vegetative growth and soil development adding to the changing conditions of the hydrologic inputs. The goal of the research is to determine the parameter values of hydrology necessary to develop a productive wetland region.

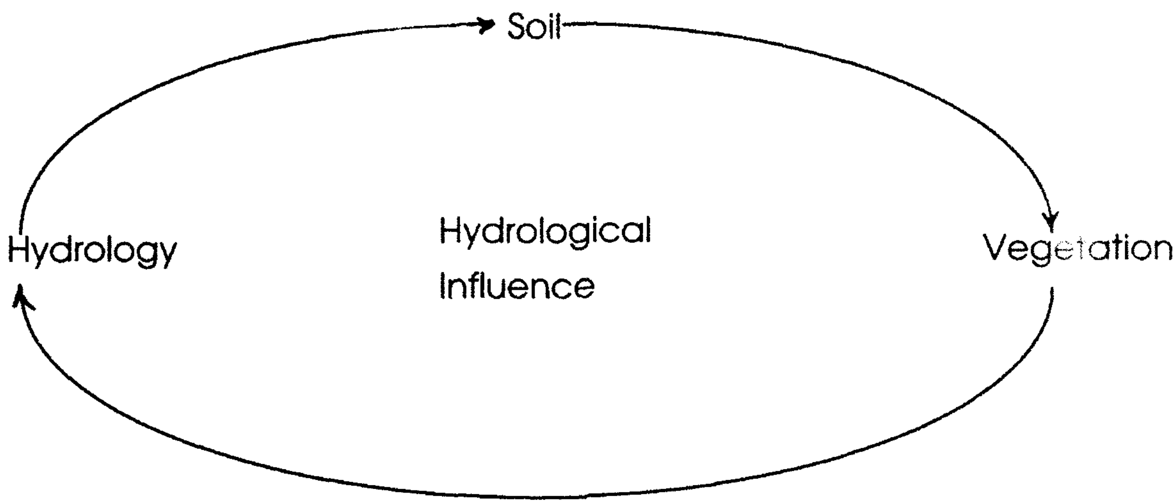


Figure 1-1: Causal diagram showing the Hydrological Influence.

Research Objectives

The use of modeling will show how a wetland is affected by altering the components of hydrology within the system. In addition, the dynamics of the hydrologic inputs will affect the abiotic factors of soil anaerobiosis and nutrient availability as well as the biotic factors ranging from vegetation to microbial communities and wildlife. Surface water, precipitation and ground water flows collectively form the total water mass of a system. It is the intent of this paper to research these parameters and determine the effects of total flow systems on the wetlands. Ultimately, adjustments to the model, in terms of external factors influencing these parameters and the development of the

wetland, will aid in the distinction of what conditions are associated with highly productive wetland areas.

Limitations of Research

This paper will concern itself with the dynamics of hydrology of inland freshwater wetlands and its components. These types of systems represent approximately 95% of the nation's resource. Additionally, the effects of the hydrologic factors will be limited to only generic soil and vegetative species of a sample wetland. It is obvious that several hundred different vegetative types are capable of adaptation to the soil and water conditions. As such, the sheer number of these species makes its impracticable to study and model in this report. Additionally, except for an occasional reference, the effects of wildlife on the functions of the systems will be ignored. Lastly, there is a significant difference in productivity rates and functions of coastal wetlands versus freshwater systems. While these systems are very important to the preservation and production of our coastal resources, the differences, especially the additional salinity effects and tidal influences, are omitted. Further investigation into these distinctly unique systems is warranted to completely understand the interaction of wetlands in the total ecological process.

Definition of Selected Terms (13:1-45):

Hydric - Soil that is wet long enough to periodically produce anaerobic conditions, thereby influencing the growth of plants.

Hydrophyte - Any plant growing in water or on a substrate that is at least periodically deficient in oxygen as a result of excessive water content.

Facultative - Those plant or animal species that have adapted to living in

either wet or dry conditions.

Obligate - Those plant or animal species that have adapted to living in wet or conditions.

Biotic - Those living entities ranging from microbial communities to plants and waterfowl which rely on oxygen for respiration.

Abiotic - Those communities which rely on other than oxygen for respiration.

Hydroperiod - represents the seasonal pattern of water level within each wetland type and signifies the rise and fall of water denoting a consistent fluctuation from year to year.

Bog - A peat accumulating wetland that has no significant inflows or outflows.

Fen - A peat accumulating wetland that receives some drainage from mineral soil and usually supports marsh like vegetation.

Overview of Study

Chapter two deals with the existing literature on wetlands and their functions. The definition of wetlands, ecological functions, and other general background information required to clarify the modeling techniques are discussed. Chapter three elaborates on how the ecosystem model is developed. An existing grassland succession model is modified to account for hydrologic characteristics of a wetland ecosystem. The modification incorporates soil and vegetation parameters often found in wetlands, as well as developing the parameters of hydrological influence into the model. Chapter four will show the finding of each experiment run on the wetland model and its importance to the creation or enhancement of wetlands. Chapter five deals with the significance of the findings and recommends areas of further research necessary to fine tune the model.

II. Literature Review

Definition of a Wetland

One of the major problems in discussing and dealing with the issues of wetlands is the apparent inability to definitely narrow the actual classification of a wetland. Several of the terms or definitions offered are very unclear or even contradictory between the wetland scientists and managers (3:21). However, proper management of and true understanding of the scientific aspects of the wetlands requires standardized recognition of definitions. Indeed, in order to mandate any regulatory action involving wetlands, an acceptable definition must be offered. Often, there are large economic impacts involved with developers wishing to expand housing, industrial parks, cities, etc., when they come against a potential wetland site. Accurate delineation of the defined boundaries of the wetlands becomes critical in: (1) determining the amount of mitigation effort required or (2) the amount of design effort required to plan construction efforts around the wetland region and the dollar costs associated with each of these.

Delineation of wetland areas is not always easy to accomplish. Wetlands are considered ecotones or transition zones between dry land and deep water. They are environments which are not always wet, although they could be, nor are they obviously dry (1:2). Wetlands which are large in size exhibit completely wet conditions with areas of deep water along with completely dry regions. Wetland definition often includes three main components. First, wetlands are distinguished by the presence of water, as a saturated soil or surface impoundment. Secondly, the soil conditions are unique and different from their upland counterparts. Thirdly, vegetation supporting the wetlands has

adapted their root structure to survive in the wet conditions of the area (3:22). It is combining these three straightforward descriptions which complicate the definitions. Although water is present in some quantity in all wetlands, the duration and depth of the water can vary to a very large extent. Many wetlands exhibit saturation in certain years, while others vary according to the seasons or time of day. This fluctuation of water levels makes it very difficult to delineate the exact dimensions at any given time. Vegetation, while adaptive to the saturated conditions do not explicitly delineate these boundaries either. Because of their facultative characteristics (adaptations enabling survival in wet or dry conditions) as opposed to the obligative characteristics (adapted to only a wet environment), their use as an indicator of wetlands is very vague.

Further complicating the definition process are the different interest groups involved, wetland scientists and wetland managers and regulators (3:24). The wetland scientists require a flexible yet rigorous definition facilitating classification, inventory, and research. The wetland manager or regulator, on the other hand, requires laws or regulations dealing with the prevention or control of wetland modification. Taking into account all the physical parameters, size, type, soil, vegetation, hydrology, coupled with differing political motives, it is easy to see why a "wetland" has a dynamic definition depending on the requirements of the parties involved. Taking all these differences into account, individuals and organizations tasked with accurately defining wetlands developed definitions generally accepted by managers, scientists and governments. One of the easiest definitions established is still frequently used by both the scientists and the managers. It evolved from the Fish and Wildlife Service in 1956 in the form of a publication referred to as Circular 39 (3:25):

> The term "wetlands" ... refers to lowlands covered with shallow and sometime temporary or intermittent waters. They are referred to by such names as marshes, bogs, swamps, wet meadows, potholes, sloughs, and

> river overflow lands. Shallow lakes and ponds, usually with emergent vegetation as a conspicuous feature, are included in the definition, but the permanent waters of streams, reservoirs, and deep lakes are not included. Neither are water areas that are so temporary as to have little or no effect on the development of moist soil vegetation.

The Circular 39 went on to emphasize wetlands which were important as water fowl habitats and included 20 types of wetlands that served as the basis for wetland classification until the 1970's. In 1979 scientists in the Fish and Wildlife Service offered a definition in a report entitled Classification of Wetlands and Deep water Habitats of the United States (3:25):

> Wetlands are lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water....Wetlands must have one or more of the following three attributes: (1) at least periodically, the land supports predominantly hydrophytes, (2) the substrate is predominantly undrained hydric soil, and (3) the substrate is nonsoil and is saturated with water or covered by shallow water at some time during the growing season of each year.

Here, the definition recognizes the wetlands as a transition between the aquatic and terrestrial zones. It broadens the three essential components of a wetland, soil, hydrology and vegetation (1:5). It is also interesting to note that two of the three attributes are qualified by "predominantly" since changes in elevation of water tables and land surface are very common to all wetlands thus having some terrestrial areas (1:5). It is not uncommon to have as much as 20% terrestrial area within a wetlands and because it is a transition zone, this aspect helps contribute to the diversity and productivity of the resource (1:5).

Wetlands concerns and considerations bridge several federal agencies. As such a common definition among those agencies is required. In fact, in 1990, a joint definition

was developed and formally adopted by the Fish and Wildlife Service, the Environmental Protection Agency, the Soil Conservation Service, and the Corps of Engineers (1:6). The Clean Water Act is the principle tool for regulating and protecting our natural wetlands, and as such call for the permitting of any dredging or fill of the waters of the United States. Because of this, the EPA has also established a set of definitions to differentiate between the natural wetlands and man-made systems to suffice requirements of section 404 of the Federal Water Pollution Control Act (1:7):

> "Constructed wetland: Those wetlands intentionally created from nonwetland sites for the sole purpose of wastewater or stormwater treatment. These are not normally considered waters of the U.S. Constructed wetlands are to be considered treatment systems (i.e., not waters of the U.S.); these systems must be managed and monitored. Upon abandonment, these systems may revert to waters of the U.S. Discharges to constructed wetlands are not regulated under the Clean Water Act. Discharges from constructed wetlands to waters of the U.S. (including natural wetlands) must meet applicable NPDES permit effluent limits and state water quality standards.
>
> Created Wetland: Those wetlands intentionally created from nonwetland sites to produce or replace natural habitat (e.g. compensatory mitigation projects). These are normally considered waters of the U.S.
>
> Created wetlands must be carefully planned, designed, constructed, and monitored. Plans should be reviewed and approved by appropriate state and federal agencies with jurisdiction. Plans should include clear goal statements, proposed construction methods, standards for success, a monitoring program and a contingency plan in the even success is not achieved within the specified time frame.
>
> Created wetlands should be located where the 'return' to the environment will be maximized (not necessarily on site) and should be protected in perpetuity, to the extent feasible, through easements, deed restrictions, or transfer of title to an appropriate conservation agency or organization. Site characteristics should be carefully studied, particularly hydrology and soils, during the design phase and created wetlands should not be designed to provide habitat and provide stormwater treatment."

Wetlands Classification

Since the early 1900's, our nation's wetlands were regionally classified, some by vegetative type and others by their hydrological components. The United States Fish and Wildlife service completed a system of classification in 1954 based on flooding depth and dominant forms of vegetation (3:616). The classification system is hierarchical based with 5 large systems. These systems are progressively divided into 10 subsystems, 55 classes and 121 subclasses (1:9). Each of these subclasses are characterized by dominant types of plants and animals. The problem with this system is that practically anything which is wet for a short duration can fit into one of these categories, including a pothole in an asphalt surface.

The goal of wetland classification "is to impose boundaries on natural ecosystems for the purpose of inventory, evaluation and management" (3:617). To accomplish this, four major objectives were identified:

1. To describe ecological units that have certain homogeneous natural attributes.
2. To arrange these units in a system that will aid decisions about resource management.
3. To identify classification units for inventory mapping.
4. To provide uniformity in concepts and terminology.

The overall results of these goals and objectives were published in the United States Fish and Wildlife Circular 39. This report categorized 20 types of wetlands under four major categories: (1) Inland fresh area, (2) Inland saline areas, (3) Coastal freshwater

Type Number	Wetland Type	Site Characteristics
	Inland Fresh Areas	
1.	Seasonally flooded basins or flats	Soil covered with water or waterlogged during variable periods, but well drained during much of the growing season; in upland depressions and bottomlands
2.	Fresh meadows	Without standing water during growing season; waterlogged to within a few inches of surface
3.	Shallow fresh marshes	Soil waterlogged during growing season; often covered with 15 cm or more of water
4.	Deep fresh marshes	Soil covered with 15 cm to 1 m of water
5.	Open fresh water	Water less than 2 m deep
6.	Shrub swamps	Soil waterlogged; often covered with 15 cm or more of water
7.	Wooded swamps	Soil waterlogged; often covered with 30 cm of water; along sluggish streams, flat uplands, shallow lake basins
8.	Bogs	Soil waterlogged; spongy covering of mosses

Table 2-1. Circular 39 Wetland Classification by U.S. Fish and Wildlife Service

areas, and (4) Coastal saline areas. It is noted again that this paper will only deal with inland freshwater systems. A description of the site characteristics included in this classification are shown in table 2-1(3:620). This classification system was the undisputed means of categorizing our wetlands until 1979 when the United States Fish and Wildlife Service published the "Classification of Wetlands and Deepwater Habitats of the United States" (5:625). This system categorized wetland with the deepwater ecosystems to create a comprehensive classification of all aquatic and semi-aquatic continental ecosystems. This new system "...is intended to describe ecological taxa,

arrange them in a system useful to resource managers...and to provide uniformity of concepts and terms. Wetlands are defined by plants (hydrophytes), soils (hydric soils), and frequency of flooding...." (3:628). Figure 2-1 shows the wetland and deepwater habitat classification hierarchy, modified to contain only freshwater inland wetland areas (3:629). The systems of this hierarchy are defined as "a complex of wetlands ... habitats that share the influence of similar hydrologic, geomorphologic, chemical or biological factors" (3:630). These categories are defined as follows:

> "1. Riverine--wetland and deepwater habitats contained within a channel with two exceptions: (1) wetlands dominated by trees, shrubs, persistent emergents, emergent mosses, or lichens, and (2) habitats with water containing ocean-drived salts in excess of 0.5 parts per thousand.
>
> 2. Lacustrine--wetlands and deepwater habitats with all of the following characteristics: (1) situated in a topographic depression or a dammed river channel; (2) lacking trees, shrubs, persistent emergents, emergent mosses, or lichens with greater than 30 percent aerial coverage; and (3) total area exceeds 8 hectare (20 acres). Similar wetland and deepwater habitats totaling less than 8 hectare are also included in the Lacustrine system when an active wave-formed or bedrock shoreline feature makes up all or part of the boundary or when the depth in the deepest part of the basin exceeds 2 m (6.6 feet) at low water.
>
> 3. Palustrine--All nontidal wetlands dominated by trees, shrubs, persistent emergents, emergent mosses or lichens, and all such wetlands that occur in tidal areas where salinity stemming from ocean-derived salts is below 0.5 parts per thousand. It also includes wetlands lacking such vegetation but with all of the following characteristics: (1) area less than 8 hectares; (2) lack of active wave-formed or bedrock shoreline features; (3) water depth in the deepest part of the basin of less than 2 m at low water; (4) salinity stemming from ocean-derived salts of less than 0.5 parts per thousand."(3:630)

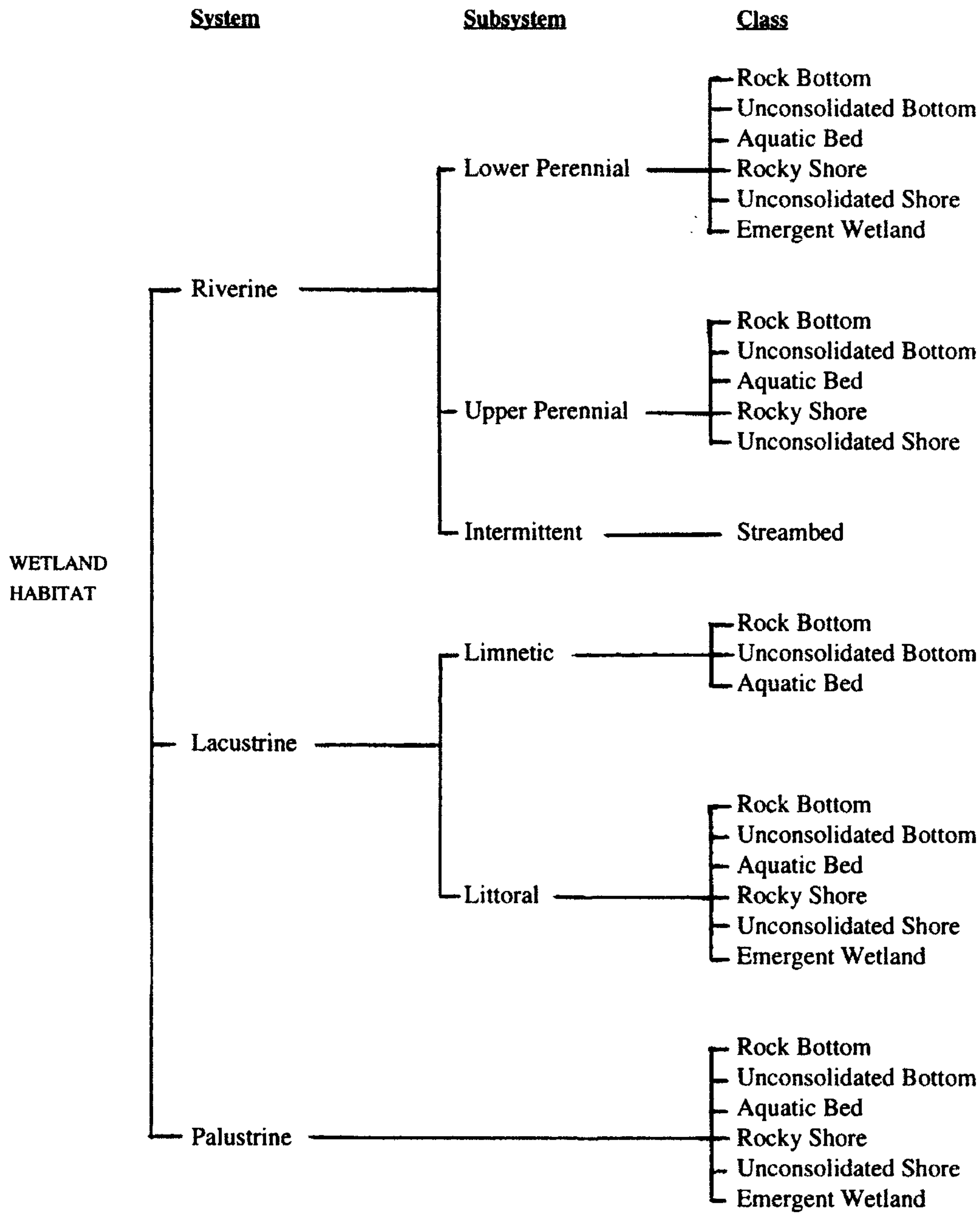


Figure 2-1. Wetland habitat classification hierarchy (3:629)

The subsystems further delineate the systems as follows:

"1. lower perennial--riverine systems with continuous flow, low gradient, and no tidal influence;

2. upper perennial--riverine systems with continuous flow, high gradient, and no tidal influence;

3. intermittent--riverine systems in which water does not flow for part of the year;

4. limnetic--all deepwater habitats in lakes;

5. littoral--wetland habitats of a lacustrine system that extends from shore to a depth of 2 m below low water or to the maximum extent of nonpersistent emergent plants (3:631).

Finally, the class describes the general appearance of the ecosystem in terms of the dominant vegetation or substrate type.

Functional Values of Wetlands

There are many differing opinions on the functional values of a wetland area both from personal and society views. Regardless of the views, science has shown that wetlands do indeed provide intrinsic value as well as ecological services (6:39). It has been shown that wetlands rank very high in aesthetic quality because of the pleasing land water interface. These typically scenic views provide variety with other types of natural or manmade areas. In addition, wetland flora and fauna have pleasing and special aesthetic appeal. Education aspects, hunting, and potential for food and drug production are additional intrinsic values (6:40-43). The ecological services are numerous with the most visible being the large amount and diversity of plant and animal life. Wetlands provide an ecological base for all aspects of life from zooplankton, worms, insects, crustaceans, to reptiles, fish, birds, and mammals. All of which feed on plant materials or one another (1:16). The system draws other animals from nearby terrestrial environments

to feed on the highly productive edge, and they are prey for animals farther away and so on. Because of this productive environment, it is estimated that 190 species of amphibians, 270 species of birds and over 5,000 varieties of plants call wetlands their home (1:25). Additionally, the wetlands act as a buffer for flood waters by being able to store and convey additional quantities of water At these times, the nutrient-rich organic and inorganic material suspended in the water are deposited and become involved in the many biochemical cycles within the wetland (6:43). Erosion control, ground water recharge, and water quality improvement are also very important values associated with wetlands.

Components of Wetlands

There are three basic components to the success of a wetland system: water, soil, and vegetation. All have individual significant importance in their own right. Emphasis is placed on the hydrology aspect and as such will be discussed last. Descriptions of soil and vegetation characteristics and functions need clarification in order to fully understand the entire role of wetlands.

Wetland Soils

In the early stages of wetland protection, soils were utilized as a delineation tool. The soil was categorized into approximately 36 soil series ranging from very poorly drained mineral soils to well drained alluvial soils. As time progressed, problems arose in this system which could not be overcome. Drainage patterns differed over very short distances which made accurate classification most difficult (5:36). However, as scientific research continued through the years, the sophisticated physical chemical and biological

processes became known. Thus the swing from drainage factors involving wetland delineation to a soil classification system occurred. In 1987 the United States Soil Conservation Service defined wetland soils as hydric, "a soil that is saturated, flooded, or ponded long enough during the growing season to develop anaerobic conditions in the upper part" (3:115). This type of condition favors hydrophytic vegetation. These hydric soils are further classified into mineral and organic soils. Mineral soils contain less than 12 to 29% organic matter while organic soils contain greater than 12 to 20% organic matter (1:30). However, depending on the source, these characteristic parameters differ by quite a lot. For example, Mitsch calls for a mineral soil to contain less than 20 to 35% organic matter (3:116). However, he also gives the United States Soil Conservation Service's definition of organic soils under two conditions of saturation, and it is presented here:

> 1. saturated with water for long periods or are artificially drained and excluding live roots, (a) have 18 percent or more organic carbon if the mineral fraction is 60 percent or more clay, (b) have 12 percent or more organic carbon if the mineral fraction has no clay, or (c) have a proportional content of organic carbon between 12 and 18 percent if the clay content of the mineral fraction is between zero and 60 percent; or
>
> 2. never saturated with water for more than a few days and have 20 percent or more organic carbon.

Any soil material which falls outside this definition is considered to be mineral soil material (3:116). Indeed, after further investigation, what Schneller refers to as organic matter, Mitsch identifies as the percentage of organic carbon.

The upper layers of a wetland typically are organic soils, also called historols while the lower levels may consist of mineral soils (1:31). There are distinct functional differences between these two types of soils. First, the bulk density is lower in organic

soils because of the high porosity associated with them, typically as much as 80%. Mineral soils show only about 45-55% porosity. Next, hydraulic conductivity is typically high in mineral soils, but the degree of decomposition in organic type soils can vary the rate of flow through the material from very high to low (3:117). Also, the organic soils tend to tie up more minerals in organic form which are unavailable for plant nutrients than mineral soils. This may be somewhat misleading in that organic soils contain more total nutrients. In most cases it is the mineral soils which contain more usable nutrients.

The most common types of organic hydric soils are peat and muck, and as such, their characteristics warrant discussion. The United States Department of Agriculture Soil Survey Manual gives a detailed description of the formation of these soils (8:10).

> In moist situations where organic matter forms more rapidly than it decomposes, peat deposits are formed. These peats become, in turn, parent material for soils. If the organic remains are sufficiently fresh and intact to permit identification of plant forms, the material is regarded as peat. If, on the other hand, the peat has undergone sufficient decomposition to make recognition of the plant parts impossible, the decomposed material is called muck. Generally speaking, muck has a higher mineral or ash content than peat, because in the process of decomposition the ash that was in the vegetation accumulates.

Organic hydric soils are classified into three groups as described by Mitsch and Gosselink (3:119). First, where two-thirds or more of the material is decomposed and less than one-third of the plant fibers are identifiable the soil is a muck (Saprists). Secondly, if less than one-third of the material is decomposed, and more than two-thirds of plant fibers are identifiable the soil is a peat (Fibrists). The third classification, mucky peat (Hemists) is where conditions between sparist and fibrist soils occurs.

The soils, whether organic or mineral, because of the inundation of water, usually become anaerobic. This loss of oxygen greatly affects the oxidation-reduction potential,

commonly called redox (1:31). The "redox potential measures the soil or water's capability to oxidize or reduce chemical substances . . . " (1:31). Oxidation occurs when a chemical releases an electron and reduction is the opposite, or the gaining of an electron (3:123). It is this factor coupled with the interactions of pH which influences the cation-exchange capacity in the different types of soil as well as physical and chemical reactions. These reactions affect the solubility of materials and thus their availability for plant uptake. It is these various transformations which occur in the wetlands that modify organic and inorganic substances (1:31).

The decomposition of this system is brought about by the microbial respiration of anaerobic microorganisms. These organisms can use substances other than oxygen as the terminal electron acceptor during the respiratory process (1:31). Although these anaerobic decomposition rates are typically only 10% of aerobic decomposition rates, it is still the process for changing original plant structure both physically and chemically, to account for the ecological productivity of a wetland. It is the loss of soil oxygen which results in the unique qualities of wetland soils contributing greatly to their functional value (1:33). This process transforms the wetlands into the most reducing ecosystem known by chemically transforming nutrients and other materials (1:33). These transformations may change organic inputs into inorganic outputs or convert inorganic inputs into organic outputs. Internal cycling of these materials is also very possible. In addition to this, hydrology plays a large role in influencing the transport of the nutrients through the wetlands (3:148). This total process is mathematically represented by an ecosystem mass balance. This mass balance is sometimes referred to as a nutrient budget. It is this input and output of nutrients and chemical transformation which greatly influence the productivity of wetlands.

These nutrients are not the same from wetland region to region. One major reason for this is the water quality entering the system. As precipitation reaches the ground it either percolates downward to ground water, returns directly back to the atmosphere via evapotranspiration, or flows as surface runoff. Each of these pathways have distinct mineral content but, after transport through each independent system until the coming together of each to contribute to a wetland, the mineral content is vastly different from the original form. Thus the concentrations found for the chemical transformations vary in each individual wetland (3:144). Several factors external of the system contributes to these changes as presented by Mitsch (3:145) and paraphrased below:

> 1. Ground water comes into contact with underground formations and, depending on the type of mineral present, determine the chemical characteristics. Soil and rock weathering, through dissolution and redox reactions, provides major dissolved ions to waters that enter the ground. The ability of water to dissolve mineral rock depends, in part, on its nature as a weak carbonic acid.
>
> 2. Climate influences surface water quality and subsequent nutrient flow through the balance of precipitation and evapotranspiration. Arid regions tend to have higher concentrations of salts in surface waters than do humid regions. Climate also indirectly affects the physical, chemical, and biological characteristics of soils and the degree to which soils are eroded and transported to surface waters.
>
> 3. Geographic Effects. The amounts of dissolved and suspended materials that enter streams, rivers, and wetlands also depend on the size of the watershed, the steepness or slope of the landscape, soil texture, and the variety of topography.
>
> 4. Stream flow/Ecosystem Effects. The water quality of surface runoff, steams, and rivers varies seasonally. It is most common that there is an inverse correlation between stream flow and concentrations of dissolved materials. During wet periods and storm events, the water is contributed primarily by recent precipitation that becomes stream flow very quickly without coming into contact with soil and subsurface minerals. During low flow, some or much of the stream flow originates as groundwater and has higher concentrations of dissolved materials. (3:145)

This shows the dynamic process which soils add to the wetland ecosystem and how those soils are influenced by external factors.

WETLAND VEGETATION

Although there are thousands of plant species in wetlands, they are a very unique type vegetation. These hydrophytes (aquatic plants) have developed unique respiratory functions. Vascular plants developed a pore space in their tissues which allows oxygen to diffuse from the aerial parts of the plant to the roots which satisfies the respiratory demand (3:164). A wetland plant is by definition "capable of growing in an environment that is periodically but continuously inundated for more than five days during the growing season" (1:33). The vast majority of the wetland plants are limited to 2 meters depth of water, however, at the extremes species have been found at depths of 7 or 8 meters (1:33). The vascular plants are divided into free floating and rooted categories with the rooted types subdivided into submergent, emergent, and floating-leaved types. These plants, as stated earlier, are rooted in soils which contain inadequate concentrations of oxygen to provide respiration. To overcome this oxygen shortage, the wetland plants developed an internal lacunae system that occupies up to 60% of the total plant's volume (1:33). The aerial portion of the plants transport diffused atmospheric gases by way of this lacunae or air spaces, to the root system. The opposite of this holds true as well, in that the root system allows diffusion of gases from decomposed materials via the lacunae into the atmosphere.

WETLAND HYDROLOGY

Hydrologic conditions of wetlands are developed through the flow of water in the form of precipitation, ground water or surface water. The characteristic of this flow into, through, and out of the wetlands and its interactions with the wetlands determines the vegetation, and most functions of the wetland (11:4). The successful creation of a wetland is highly dependent on the hydrology. It is an important factor to both biotic and abiotic functions. The biotic components, vegetation and animals alike, greatly affect the overall function of a wetland. Vegetation controls water conditions through sediment trapping, nutrient retention, peat building, transpiration, water gains and losses, depth, velocity and circulation patterns within the system (3:69/1:21). The hydrology also determines the abiotic function through water depth, aerobic and anaerobic soil conditions, composition and particle size of the soil, as well as the chemistry and velocity of the water (1:21). In terms of the creation or restoration of a wetland, "hydrology is probably the single most important determinant for the establishment and maintenance of specific types of wetlands and wetland processes" (3:68/11:5). So important are these conditions that even the slightest change in one factor of the hydrology can have a massive effect on the biotic richness and ecosystem productivity (11:5).

The hydroperiod represents the seasonal pattern of water level within each wetland type. It typically signifies the rise and fall of water denoting a consistent fluctuation from year to year. This period depicts the stability of, and to an extent, the characterization of each type of wetland. To determine the hydroperiod, all potential water sources are defined, as well as changes in terrain and proximity to other bodies of water (3:72). The hydroperiod is defined as the result of the following three factors. First, the balance between water inflows and outflows; second, the topographical contours of the surrounding landscape and lastly, subsurface soils, geology, and groundwater conditions.

The first factor defines the overall water budget, while the other two express the ability of the wetland to store water (3:76).

The water budget serves to identify all hydrologic components of any wetland. Figure 2-1 shows a generalized water budget depicting all the parameters associated with the hydroperiod. The hydroperiod is a dynamic entity and all the parameters of a water budget are not applicable in every wetland. There are great differences in the inflows and outflows of water. Table 2-1, as presented by Mitsch, expresses the dynamics of each of the water budget parameters. Precipitation includes both snowfall and rainfall and is a strong factor in establishing a wetland area when it is in excess of losses such as evapotranspiration and surface runoff. The precipitation, on its way to the wetland, is either intercepted by the overhead vegetation (interception) or passes through. Throughfall refers to that water which actually passes through the vegetation and reaches the substrate or water below. This variable is quite difficult to define, as it depends on several factors. The total amount of precipitation, its intensity and the character of the vegetation such as its stage of development, the specific type and stratification of the vegetation, all influence the total amount of water intercepted (3:81). Studies have shown that the amount of precipitation intercepted varies between 8 and 35 percent with an accepted median value of 13 percent for deciduous forests and 28 percent for coniferous forests. Grasslands and marshes, during periods of maximum growth have interception values similar to the forests, ranging from 10-35 percent (3:82). The intercepted water is lost back to the atmosphere via evaporation or it is directly absorbed into the plants themselves.

Surface inflows influence wetlands through various sources. There is overland flow, that water which is nonchannelized, usually occurring after a rainfall event or the thawing of frozen precipitation. Channelized stream flow results if the area is influenced by a drainage basin. In this case, water may enter the wetland most of or all year long. Also,

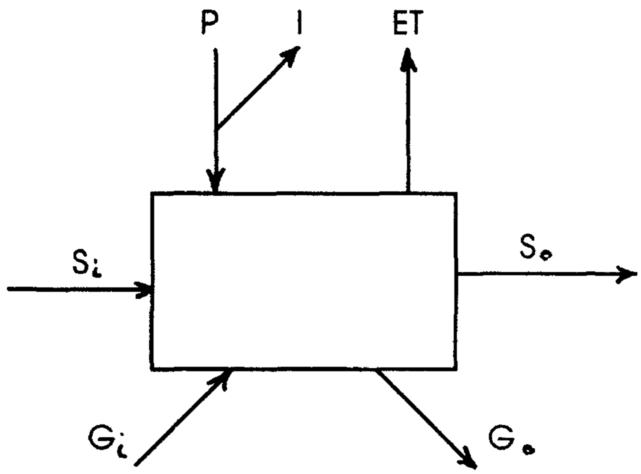


Figure 2-2. Generalized water budget. P = precipitation, I = interception, P_n = net precipitation, ET = evapotranspiration, S_i = surface inflow, S_o = surface outflow, G_i = ground water inflow, G_o = ground water outflow.

Component	Pattern	Wetlands Affected
Precipitation	Varies with climate although many regions have distinct wet and dry seasons.	All
Surface Inflows and Outflows	Seasonally, often matched with precipitation pattern or spring thaw; can be channelized as stream flow or nonchannelized as run-off; includes river flooding of alluvial wetlands	Potentially all wetlands except ombrotrophic bogs; riparian wetlands, including bottomland hardwood forests, and other alluvial wetlands, are particularly affected by river flooding
Groundwater	Less seasonal than surface inflows and not always present	Potentially all wetlands except ombrotrophic bogs and other perched wetlands
Evapotranspiration	Seasonal with peaks in summer and low rates in winter. Dependent on meteorological, physical, and biological conditions in wetlands	All

Table 2-2. Major Components of Hydrologic Budgets for Wetlands.

wetlands are often integrated parts of a river or stream. As in instream freshwater marshes, the wetland forms a wide shallow expanse of the river channel. Such systems are greatly influenced by the river's seasonal stream flow patterns. Lastly, at times the wetland can receive surface flow from episodic pulses of floods or rivers and streams which are otherwise not hydrologically connected to the wetland system. These surface influences are very difficult to estimate without a large amount of data. However, since it is impractical to gather the data and this water input is a significant contributor to the wetland water budget, several equations are employed to estimate the amount of water contributed (3:85).

Ground water interaction with the wetlands is the third component of the water budget. There are instances where ground water may heavily influence a wetland as well as locations where ground water plays hardly any role in the budget. Ground water influence has been cited as one of the most important attributes of wetland development even though not all wetland types are dependent on it (3:93). There are two ways in which ground water influences the wetland, recharge and discharge. Recharge occurs when the wetland area is above the water table of its surroundings. Under this condition, water will flow out of the wetland through the ground and ultimately contribute to the water table. Discharge is just the opposite. It occurs when the wetland is lower hydrologically than the surrounding ground water levels. In this case ground water will flow into the wetland region. The influence of ground water is also hard to pin down. It is dependent on the hydraulic conductivity of the soil. This parameter of ground water flow is very difficult to ascertain, especially in organic type soils (3:95). The hydraulic conductivity for this type soil changes as a function of the decomposed biomass. The bulk density of fiber contents controls the conductivity of the peat soil. The value decreases as the fiber content decreases through decomposition. That is, as the fiber

decomposes, the hydraulic conductivity of the soil becomes lower and lower. In fact, water passes through fibric (poorly decomposed) peat an order of 1000 times greater than a sapric (thoroughly decomposed) peat. In fact, it is been noted that the hydraulic conductivity of peat can vary up to 10 orders of magnitude or between 10^{-8} through 10^{2} cm/sec (3:95). Darcy's law is the fundamental rule which describes the flow of ground water through a system. It is dependent on two factors: (1) the slope of the piezometric surface, called the hydraulic gradient and (2) the capacity of the soil to conduct flow, called the hydraulic conductivity. This law allows the rate at which water flows into or out of a wetland to be measured.

Evapotranspiration is an important part of the water budget as well. Even though it does not add any water to the wetlands, it can play a major role in the loss of water from the wetlands. However, the question of whether or not the vegetation of the wetlands increases or decreases the amount of water loss is not clearly answered. Many different studies have shown individual wetlands to both decrease and increase the amount of water loss due to the transpiration of the vegetation. Therefore, the conflicting measurements led to conclusions by botanists E. Linacre and S. Bernatowicz that neither the presence of nor type of vegetation had any major influences on evaporation rates during the active growing season (3:102). With this in mind, to account for the evapotranspiration water loss, a version of Dalton's law is employed. This accounts for water vaporizing from the water or soil of a wetland along with that moisture which passes through the vascular plants to the atmosphere. Dalton's law determines the rate of evapotranspiration based on the proportional difference of the vapor pressure at the water or plant surface and the vapor pressure in the overlying air (3:97).

Wetland Models

Little efforts in wetland models existed prior to the discovery of their usefulness to and necessity to maintain our ecological environments. Even after the emphasis on wetlands increased, modeling of them was a slow process because of the complexity of the system. The models would have to consider both terrestrial and aquatic systems. Since the mid-1970's, the modeling effort has increased as the knowledge of the systems increased. According to Michael J. Duever, the unique hydrologic characteristics of wetlands depends on the topography, soil, and vegetation which create the necessary water depths and duration of inundation (22:9). The distribution of water, as discussed earlier, is precipitation, surface flow and ground water flow. The following model (modified from Duever's wetland hydrology) illustrates these three parameters and their relationship to each other as well as to soil and vegetation. It is the hydroperiod which is

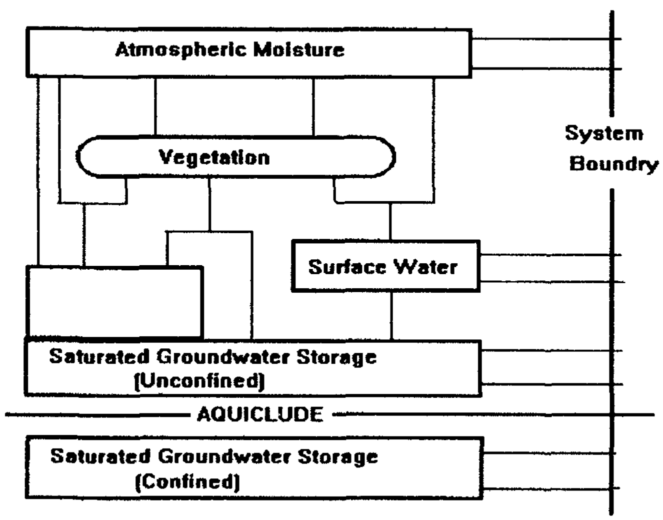


Figure 2-3. Simple model of hydrological parameters.

the dominant factor controlling the existence of and plant community composition, and is a major component in a wetland's development model (23:123).

Various models of wetland ecosystems exist depicting certain parameters in site specific, fully developed characterized wetlands. William Mitsch presents a model detailing forested wetland production with respect to water level and nutrient flow. This is a simplified model dealing with only a single nutrient level and three different hydrologic conditions. Nonetheless, the results show that the hydrologic factors each produced a different amount of biomass, with all other factors constant. There are also a multitude of models or data pertaining to the specific types of wetlands in various regions throughout the world (see Wetlands by W.J. Mitsch, et al for details).

Ecosystem Succession:

To understand both the grassland succession model and the resulting wetland ecosystem model, background information on ecosystem succession warrants discussion. Succession is the processes ecosystems undergo during progression towards a mature and stable climax (10:9). This is a dynamic process showing the development of one state of conditions through additional stages until an equilibrium exists between the living community and its physical environment (9:15). A typical succession, or sere, consists of an initial stage followed by one or more intermediate stages until it progressively reaches its climax stage. Robert H. Whittaker's definition of general succession patterns of an ecosystem is paraphrased below: (Taken from a reprint of Communities and Ecosystems, 9:17)

1. The soil first progressively develops, increasing in depth, increasing organic content and differentiation of layers as it progresses towards the final mature soil of the final community.

2. Productivity of the plant community, in terms of organic matter, increases with the development of the soil, which leads towards increase uses of environmental resources.

3. As progression continues, the microclimate within the community is increasingly determined by the community characteristics.

4. Species diversity increases from simple to more complex communities.

5. Populations rise and fall and replace one another. The replacement rate slows as smaller short-lived species are replaced with larger longer-lived ones.

6. The relative stability of communities consequently increases. Early stages are dominated by populations which rapidly replace one another, progressing to the final community which is stable and dominated by longer-lived plants which maintain their populations and communities.

In these terms, does a wetland follow true successional behavior? This has not been the case in most wetland areas (7:50). These systems are hydrologically pulsed and thus not given the opportunity to develop the proper conditions to follow a true sucessional path. There is evidence through the study of wetlands, that allogenic and autogenic perturbations continually change the behavior of the systems and that a succession towards a climax is unrealistic (10:9).

However, succession does occur within the wetland ecosystem. It has a different pattern, or method of occurrence, in the form of hydrologic pulses or perturbations. If a wetland were receiving constant rates of flow for all its parameters, it indeed would develop into a mature ecosystem with limited variation of species throughout the rest of time. Nature, though, does not supply constants with such consistency and thus change will always occur. It is the rate of change that governs the diversity and production of a

wetland, and specifically the changing hydrologic pulse that has enabled them to persist for thousands of years (7:50). E. P. Odum summarizes succession as an orderly process of community development that involves changes in species and the community over time. It results from the modification of the physical environment by the community even though the physical environment determines pattern, rate of change, and sets the limits of the system (9:35). This really defines succession in general, accounting for wetland activity as well as terrestrial and aquatic activity.

III. Grassland Ecosystem Succession Model

Ecosystem Succession Model

In the natural environment, there are literally hundreds of different and complex attributes that make up individual ecosystems. Trying to model these functions is very difficult at best. There are, however, several models that break down the ecosystem and model its behavior in simplified terms. Luis T. Gutierrez and Willard R. Fey succeeded in doing just that. They developed an accurate and widely accepted model detailing the ecosystem dynamics of secondary autogenic grassland succession. The model is able to predict, with modest accuracy, the behavior of variables in terms of growth, decline, oscillation, ect., through time (9:42). The fundamental ecological variables of the system are defined and their interactions with one another are simulated to show the progression of ecosystem succession.

Gutierrez and Fey make use of extensive causal loop diagramming to detail the feedback dynamics of their model, hereafter refered to as GRASSM. Figure 3-1 shows the basic development of GRASSM in terms of four general feedback loops of the system. The actual dynamics of these loops are described as follows. First, the negative feedback loop in the lower left corner details the systems production abilities. It shows how primary production is regulated as soluble inorganic nutrients increase and decrease in the soil. Secondly, the positive loop in the lower portion accounts for nutrient recycling within the system. It explains the functions which provide sustained reproduction and growth rates of the standing crops through time. The upper portion of the Figure represent the community controlled growth dynamics of actual ecosystem succession. The positive inner loop details the biomass growth, showing how increased

primary production increases community biomass which has a positive influence on the amount of primary production.

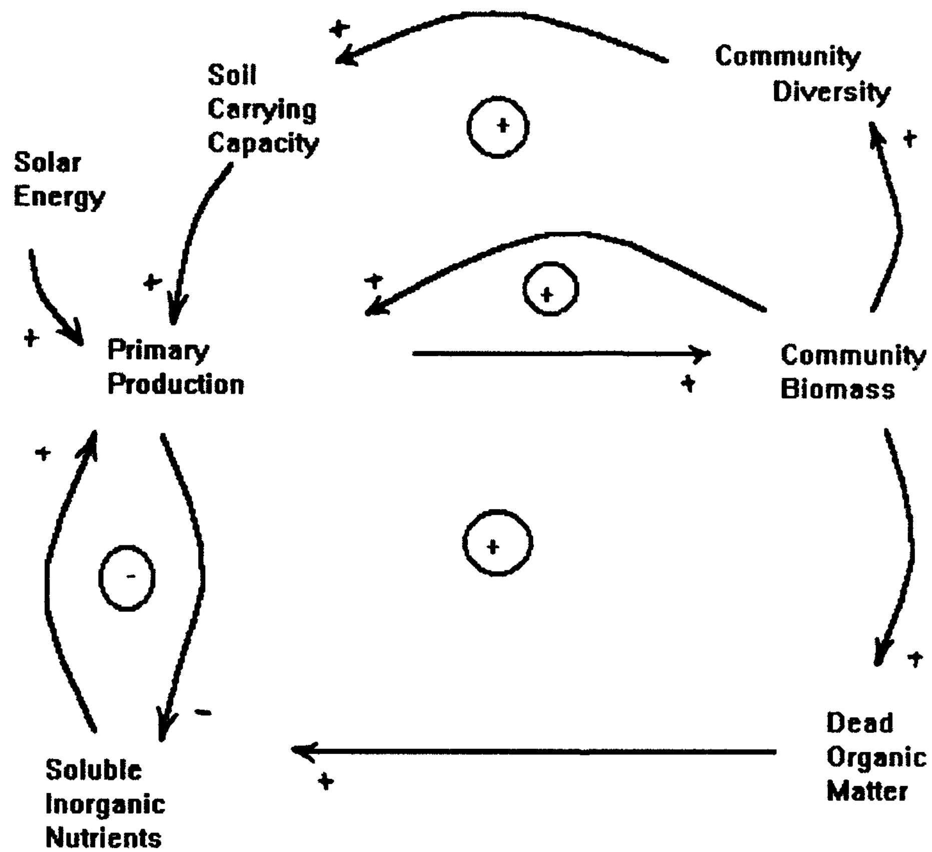


Figure 3-1. Causal diagram showing the basic dynamic process of grassland succession model (9:46).

The positive outer loop details the development of community diversification. It is a function of the soil carrying capacity and energy input. As the soil becomes saturated, the energy entering the system is reallocated from producing additional existing plant biomass and is utilized to create new diversity. These new species have the ability to increase soil carrying capacity which effects the biomass, which then effects the diversity, as shown in the loop. Again, this causal diagram shows both the positive and negative

feedback loops associated with the system in very simplistic terms. The arrows indicate direction of influence and also represent a time delay of the function. The actual dynamics of each loop are represented in expanded causal diagrams and their operations explicitly described in Ecosystem Succession by Gutierrez and Fey (9:44-100). Explanation of each loop will be described as it relates to the wetland model and discussed further on in this study. Deviations to the base grassland model are explained as the wetland modifications to GRASSM are developed.

Grassland Succession Model Verification

Each of the four loops of Figure 3-1 represent specific dynamics of the system, and joined together, they form the frame work of GRASSM. The system dynamics concepts of the causal diagram were transformed into a mathematical format and numerically quantified to provide the means of simulating the succession of the particular ecosystem. The approach used by Gutierrez and Fey to quantify the parameters is as follows: "to construct a model which is theoretically (and structurally) sound, to quantify the model relationships with reasonable or hypothetical numerical values, and to exercise the model in order to detect sensitive parameters that merit more accurate field estimation (9:95)." The equations and parameter values were employed into a computer simulation software package called dynamic models (DYNAMO) which was specifically designed to provide digital simulation of feedback dynamics. Once the model was fully developed and tested, several experiments were run to see how the ecosystem responded to natural and anthropogenic perturbations.

The platform for building a wetlands succession model is the work completed by Gutierrez and Fey. A complete and accurate representation, capable of producing the same results of the DYNAMO model was developed using the Systems Thinking,

Experimental Learning Laboratory, with Animation (STELLA) software as developed by High Performance Systems. STELLA also provides digital simulation of feedback dynamics models.

Once GRASSM was translated into the STELLA format, it simulated the same results as the DYNAMO version. Further verification of GRASSM occurred when four of the fifteen original experiments performed by Gutierrez and Fey were successfully duplicated. The STELLA flow diagram and the results of the five computer simulations are shown in appendix A.

Understanding the Dynamics of the Model

GRASSM is separated into three separate sectors: nutrient recycling, community diversity and energy flow, which are all linked together to produce the overall dynamic picture. GRASSM's compartments are built on three simplifying assumptions of the physical environment: A constant temperature, water supply, and light intensity. The major compartment, nutrients recycling loop, is comprised of five major sectors: producers biomass, consumers biomass, decomposers biomass, organic nutrients and soluble inorganic nutrients as shown in Figure 3-2.

The plant biomass (producers), because of the constant environment, will grow and decline at certain rates. Until the grasses die or are grazed away, plant biomass is accumulated on the soil as standing crop. The rate of growth of this level is dependent on replacement growth rate and new plant growth rate. To keep replacement growth functioning, there must be available energy and absorbable nutrients. This means that either one of these components can limit replacement growth if it is absent from the system. The energy limiting replacement rate is a function of the possible energy plant growth rate and the indicated replacement plant growth rate. The latter is described as an

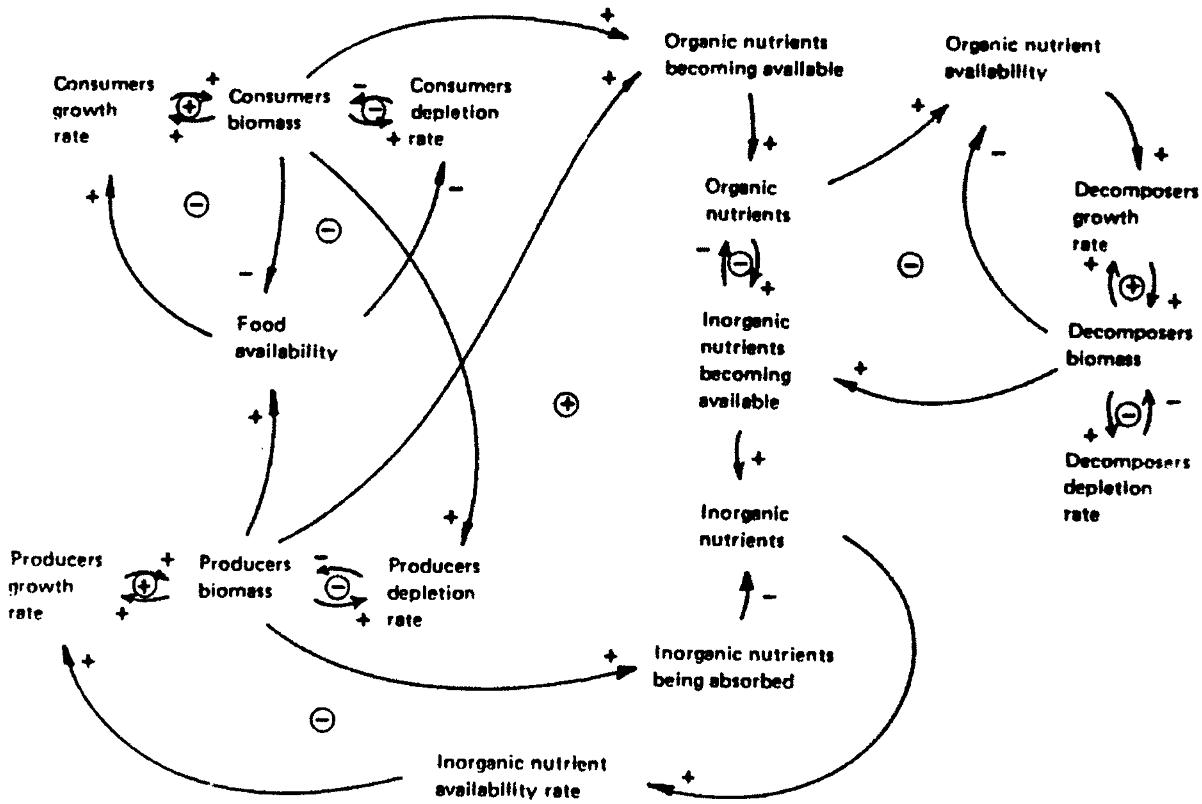


Figure 3-2. Nutrients recycling loop.

exponential average of the plant decay rate, meaning that the replacement is a function of the rate of death. The former uses the photosynthesis process and the energy drawn form stored pools called plant vigor. This vigor accounts for the energy not utilized in the photosynthesis process or for diversification of species. To account for the availability of nutrients, the plant biomass is shown to be proportional to the reservoir of soluble inorganic nutrients in the soil (those which became available from the decay of biomass). In other words, the production rate is limited in proportion to the availability rate of the nutrients.

New plant growth occurs if there is an excess of available energy and nutrients and also if there is available space or soil in which additional growth can be attempted. Therefore, the new plant growth rate is represented as the minimum of the limited nutrients available or the net new plant growth capability. The nutrient limiting function is a non negative number and is the maximum of zero or the remaining nutrients available after replacement growth is completed. The new plant growth is a percentage of the gross new plant growth which is not lost to plant respiration. This gross production is a function of the soil carrying capacity, which will be discussed later in this section. An important component of this net new growth rate is the fact that new growth is not instantaneous. Therefore, this value must be delayed, or smoothed, to reflect the actual time delay in terms of growth.

The depletion rate of this standing crop depends on the decay rate of the biomass and the consumption rate of consumers. The decay rate follows a pattern of exponential decay with an average delay of six months. The consumer consumption rate depends on the density and the growth rate of consumers. The consumer population is an aggregate level lumping all kinds of primary and secondary species. However, the level of consumers grows and declines in response to the availability of grasses as depicted in the causal diagram, Figure 3-3.

As either the plants or animals die, the dead organic matter must be broken down to complete the cycling of nutrients back to soluble inorganic form. The decaying biomass is gradually broken down by the decomposers. There is a complex process involved which prohibits its representation by a simple first order time delay. A more accurate representation of this is the complete transformation of dead biomass to nutrients formulated by a third order delay. The level of the decomposers is also going to vary and depend on the level of organic matter which is available. This group of functions represents the closed loop of the decomposers. This loop depicts the release of nutrients back to the soil where they once again can become available for utilization by the producers.

The rate of the nutrients becoming available is described as a function of the decomposers, as stated above. As the decomposed organic matter is converted to soluble inorganic nutrients, they are consumed again by the producers at a rate proportional to both the replacement and new plant growth rates. In other words, the rate at which nutrients are depleted equals the rate at which they are absorbed by the plants, starting a new cycle. This process completes the nutrients recycling loop as shown in Fig. 3-2. The nutrients will be recycled back into the system regardless of which pathways they originally flowed through.

The next compartment is the community diversification loop. This section accounts for the ability of the biotic community to increase the carrying capacity of the physical environment. In this ecosystem, the soil carrying capacity describes the ability of the soil to support additional biomass. GRASSM assumes that increments in soil-carrying capacity are effectively brought by the diversification that follows a buildup in biomass and permits the occupancy of additional species in the environment which, in turn, encourages further growth. Diversity decreases when species disappear and it increases with the emergence of new species and/or substitution of those which have vanished.

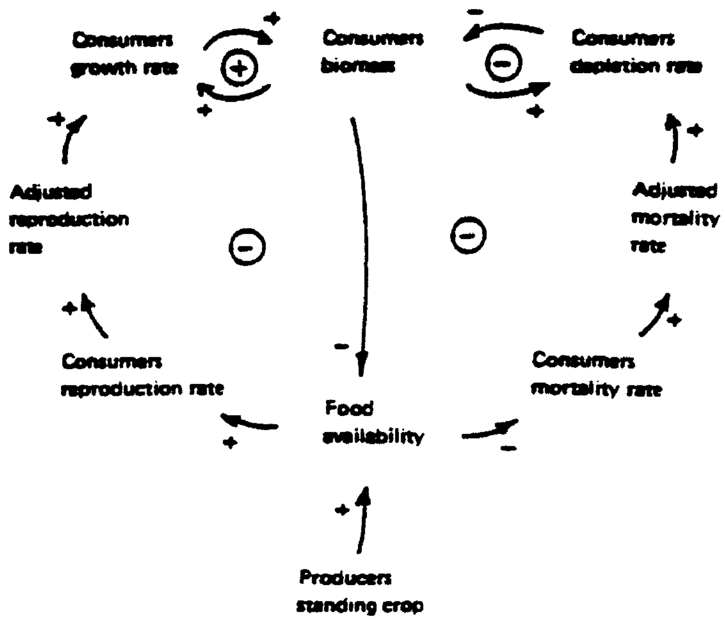
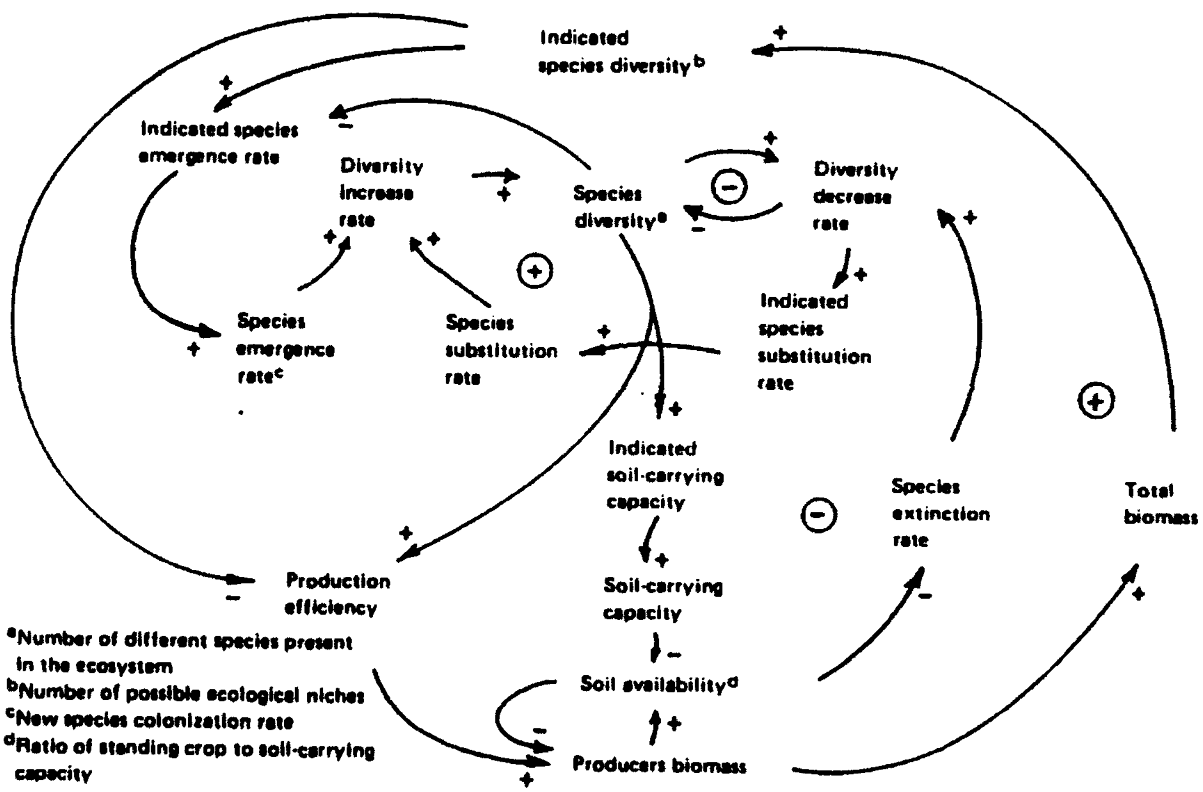


Figure 3-3. Consumers biomass feedback loop.



[a]Number of different species present in the ecosystem
[b]Number of possible ecological niches
[c]New species colonization rate
[d]Ratio of standing crop to soil-carrying capacity

Figure 3-4. Community diversification feedback loop.

During succession, species come and go based on the changes in total biomass accumulation. As species vanish because of successional change, they are replaced with new ones which are better adapted to the conditions. Therefore, as the system approaches climax, both the increase and decrease rates should approach zero. Figure 3-4 depicts this feedback loop. The soil availability index, first seen in the net new plant growth rate as a function of soil carrying capacity, is an indicator of conditions towards existing species. The value of the index ranges from zero to one. When at zero, it is indicative of a new successional stage which means conditions are changing, competition increases and as a result, existing species will begin to disappear. On the other hand, if the index is close to one, the system is mature and stable, indicative of a zero species decrease rate. Therefore, the species extinction is also a function of the soil carrying capacity.

In order for the diversity to increase, both species substitution and the emergence of additional new species have to be accounted for. Two resources are required for this to take place: biomass and energy. These factors are limited similar to those limits imposed on the growth process. Species substitution is a function of the indicated substitution rate and the possible substitution rate. Because the indicated rate replaces those species which have been lost through successional development, it is equal to the value of the species' diversity decrease rate, after a substitution delay. The possible rate of species substitution is a function of the availability of energy for diversification, which is that energy left over after all growth work is accounted for. The indicated species emergence rate, on the other hand, represents the new species brought about by the ongoing buildup of total biomass. At any given successional stage, further accumulation of biomass in the ecosystem is indicative of increased species diversity in the near future. This shows how biomass influences diversity. It also indicates previous increase in diversity which produced increased carrying capacity which in turn led to the present buildup of biomass. Therefore, the increments in species diversity are roughly proportional to increments in

total biomass as succession goes on. Their relationship is nonlinear with the biomass ceasing to generate further diversity after a certain point is reached due to several factors: Increased organism size, complexity of life histories, and interspecific competition resulting in the elimination of some species. Time is also a factor in the diversity because it is not feasible to assume that new species will emerge right as the time conditions become favorable. The actual time may be several years after conditions change. For this reason the new species emergence rate is smoothed over a period of time.

The preceding accounted for the effects of biomass on diversity. Now it is shown how diversity influences biomass. When the biotic community diversifies, it exploits a greater number of specialized niches in the soil, modifying it as it does so, thus increasing its carrying capacity after some period of time. The feedback loop between biomass and diversity is positive, but this gain gradually vanishes as one or the other causes the soil carrying capacity to reach its maximum value. This describes the entire plant production process and its efficiency within the system. As the diversity increases, the production decreases and vice versa, according to the feedback loop. Therefore, the production efficiency factor is a function of the relative diversity.

The third compartment of the model is the disposition of energy flow through the producers which is neither used for growth or diversification. Figure 3-5 shows the energetics of the model depicting how the energy is utilized. The excess energy is stored as potential energy stored in various forms (biochemical diversity, genetic diversity, etc.) which is lumped together as an energy level called plant vigor. The energy can be stored for a limited time only before it is dissipated in performance of other quality functions or becomes fossilized. In either case, after a certain period of time it is no longer available as a supplementary source of energy for production purposes. The plant vigor loop accounts for this excess energy. This portion of the model also verifies whether the flow of energy through the producers is fully accounted for. While the ecosystem is in steady

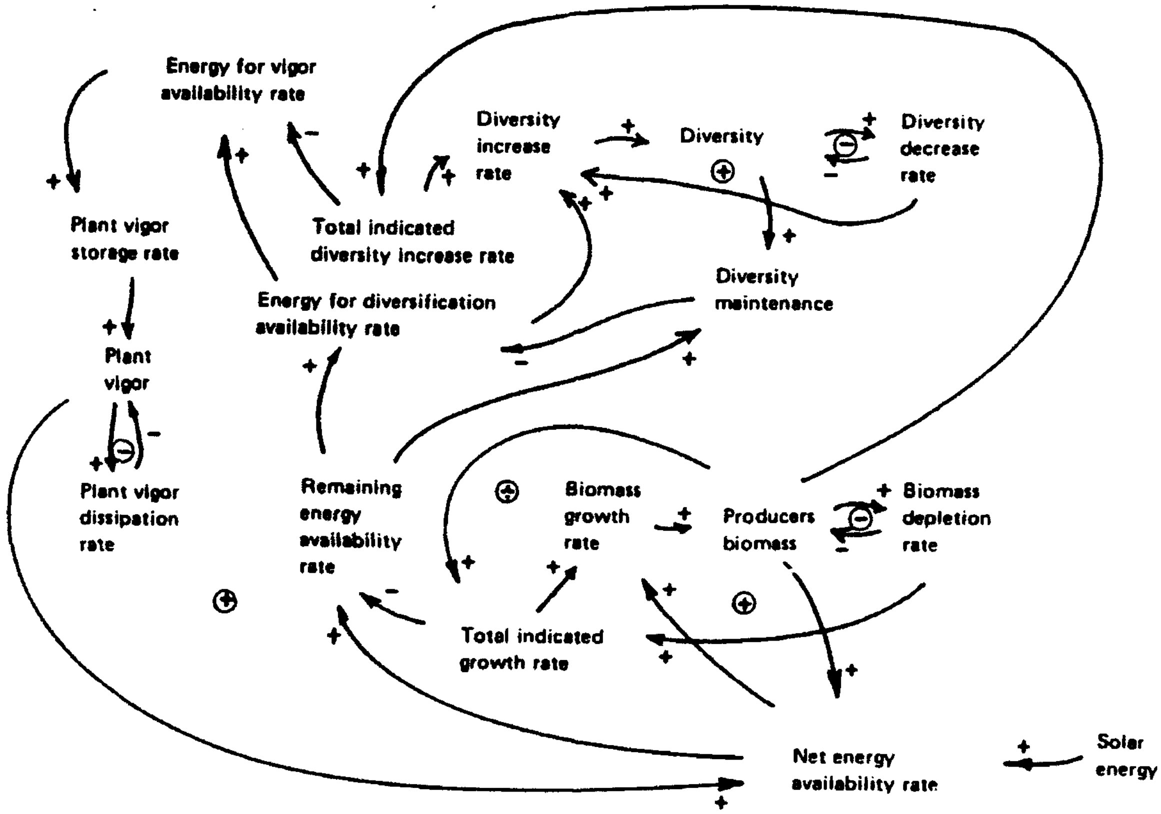


Figure 3-5. Energy feedbak loop.

state, the difference between the rates of energy flow in and out of the ecosystem should be close to zero. The energy balance loop shows how that function is represented.

The previous paragraphs synopsized the functional workings of GRASSM. Complete descriptions of actual equation relationships are available to the reader in Gutierrez and Fey's book, Ecosystem Succession. As GRASSM is manipulated to account for the effects of differing water conditions, the actual changes in model structure will be identified and documented.

IV. Wetland Model

Introduction

Gutierrez and Fey's model, GRASSM, described the interactions of a grassland ecosystem throughout its successional development. This study attempts to modify that model to simulate wetland conditions and its evolvement through successional development. Once established, the new model can be tested under different constraints to determine which conditions result in a healthy, productive ecosystem by depicting the plant biomass growth. By modifying the parameters of GRASSM to reflect that of a wetland development, managers across the Air Force can input their site specific values of water and nutrient flows and topographic layout to determine the overall expected health of the system.

Overview

This chapter deals with the development of a wetland model using GRASSM as a base from which to build. Figure 4-1 shows the four sections in which hydrology affects the model. Auxiliary variables depicting the influence of hydrology on these compartments are added to WETM, as shown in figure 4-2. The following pages explain the limitations of this model and the steps taken to convert the parameter values from GRASSM to WETM. Table 4-1 shows the auxiliary variables which were modified to construct WETM, while table 4-2 shows the new auxiliary variables added to the model.

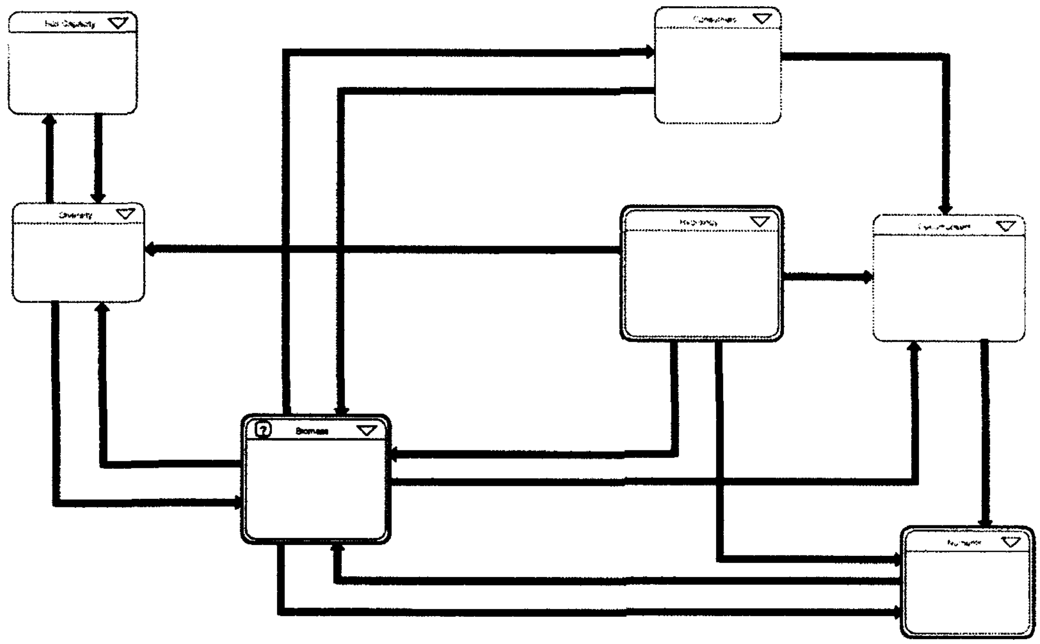


Figure 4-1. Hydrological affects on the model.

Limitations

The original model was constructed around three constants: temperature, light intensity and water supply. The wetland model incorporates one of these constants, water, into the model and modify the remainder of the parameters to account for the impact of hydrology on the system. However, this model, WETM, will not cover all aspects of all wetlands. It is developed to simulate a generic wetland, showing that hydrology plays an important role in its development. WETM will not be specific in identifying particular types of wetlands based on hydrology for classification purposes.

There are several areas of limitation to this model. First, there is no feedback of the other compartments on the input of water. This means that as hydrology affects the development of the system, that development does not affect or alter the hydrology inputs. This is a simplifying assumption incorporated so as not to alter the structural integrity of the original model. If this assumption were not made, feedback loops from

diversity, nutrient flow, total biomass, soil carrying capacity, and others would have to be developed. This is a tremendous task, one which might be considered in follow on work.

Next, WETM is not species specific. That is to say, specific species may have values associated with them that differ from those used during development. For example, the energy requirements for the wetland are based on an average standing crop of an average wetland. These values could vary significantly if specific species are

PARAMETER	DESCRIPTION	GRASSM VALUE	WETM VALUE
PDD	Plant decay delay	6	6
NAD	Nutrient absorption delay	3	Tbl Func
PDRSD	Plant decay sm. delay	12	12
INGAD	Ind new growth adj delay	6	5
DDMIN	Decomposition delay min	6	13
DDS	Decomposition delay slope	6	13
DRD	Decomposers response delay	3	3
NCRD	Nat. Consumers resp delay	6	6
NPRC	Nutrient to plant req coeff	0.03	0.0155
ONDRC	Org nutri to decomposer req	0.5	0.218
PNCRC	Plants to nat consumers req	147.1	19.84
NCPRC	Nat consumer-plant req	14.7	1.98
PPMT	Plant production multiplier	Tbl Func	Increased
NCRT	Nat consum reproduction tbl	Tbl Func	Same
NCMT	Nat consumers mortality tbl	Tbl Func	Same
SED	Species emergence delay	12	6
SMRN	Species extinction rate norm	0.01	Tbl Func
SSD	Species substitution delay	60	30
ISEAD	Ind spec emerg adj delay	60	30
SSCAD	Soil carrying cap adj delay	60	30
ESRC	Energy to species req coeff	1	1
EFR	Energy fixation rate	2	2
EPRC	Energy to plant req coeff	1	0.24
BSD	Total Biomass sm delay	12	12
PVDD	Plant vigor dissipation delay	12	12
DIVMC	Diversity maintenance coeff	0.1	0.05
PMC	Plant maintenance coeff	0.01	0.49

Table 4-1. Changes in model constants

selected to populate the wetland. In order to incorporate this feature, further refinement of the parameter values are required.

Finally, the effects of soil development and its ability to support diversity is extremely simplified in this model. Soil development in wetlands is very complicated. Further development is required in this area to accurately reflect its influence on the entire ecosystem.

PARAMETER	DESCRIPTION	WETM VALUE
WL	Water Level	Range, 0-5
DDWL	Decomp to Depth of WL	Tbl Func
AFR	Avg Flow Rate	Range, 0-20
NI	Nutrient Import	Tbl Func
NE	Nutrient Export	Tbl Func
HSM	Hydrology to Species Mult	Tbl Func
IDIVH	Ind Diversity with Hydrolo	IDIV*HSM
SMWL	Species Mort due to Water	Tbl Func

Table 4-2. Auxiliary variables added to WETM

Methodology

Since the original model called for a constant water supply, there are no variables depicting its influence on the productivity of the system. The first modification, therefore is the addition of a level representing hydrology. This must be integrated into the operation of the system, changing it from a grassland representation, to a depiction of wetland development. The hydrology will interface with the four major levels of plant biomass, available nutrients, species diversity and decomposers.

Hydrology

There are two main auxiliary variables added to the original model to account for effects of hydrology on an ecosystem. These are the water level, WL, and the flow rate through the wetland, AFR. Figure 4-2 shows how these parameters interact with the other variables in the model. In constructing these variables, it is important to note that

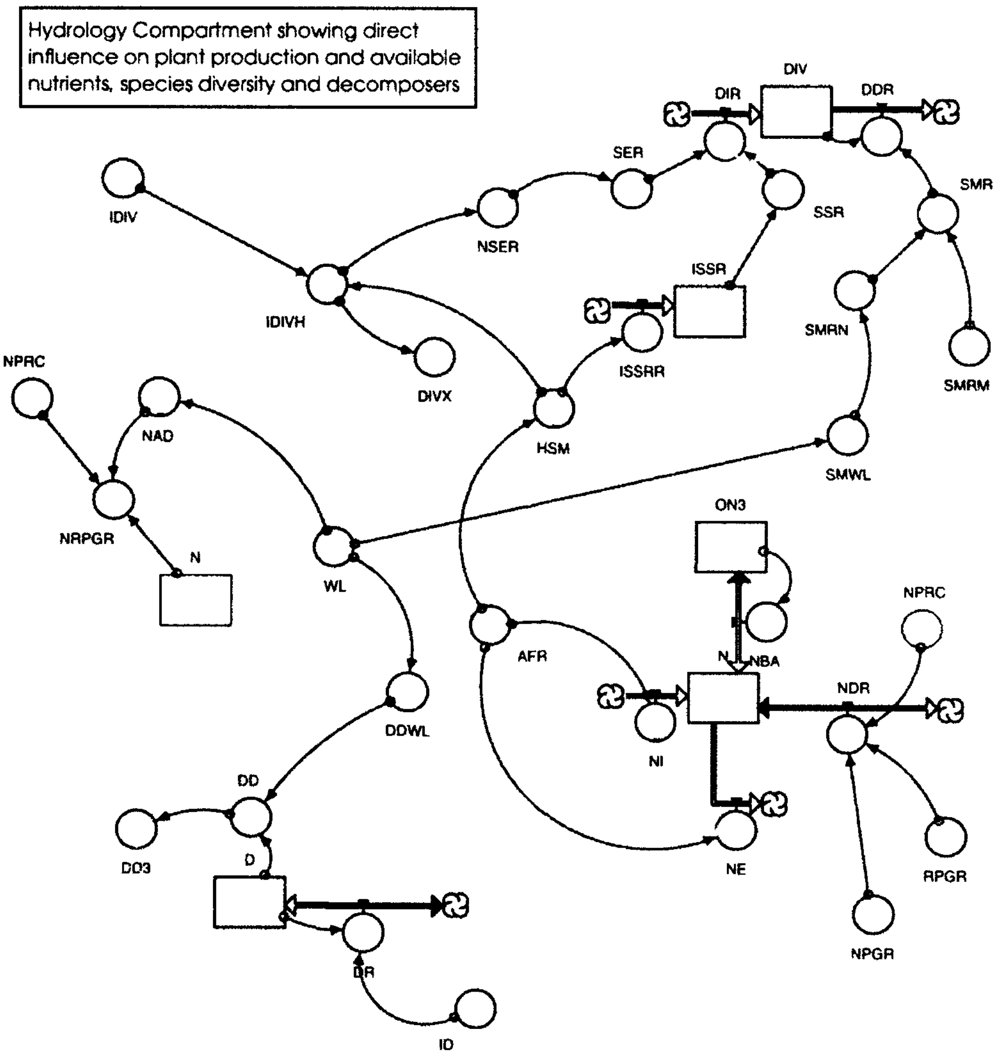


Figure 4-2. Parameter changes to model

they in no way change the structural aspect of the original model. Since there are no feedback loops into levels associated with the variables, no operational parts of WETM exhibit influence on the water flowing through the system. This is a simplification of water influence in a wetland, however, it is appropriate for the purpose of this study.

Hydrology is a very important influence on the development of wetlands in many different ways. One such way is the effect it has on the building of organic material because of the very slow decomposition time of organic material under anaerobic conditions. This also affects the height of the water table, storage capacity, and the rate of flow through the wetland. In his development of wetland models, Mitsch has shown that while the building of soil is a factor in wetland function, the influence to the building process takes many years to develop. His study shows that after 100 years, depending on the conditions of flow, the accumulation of peat did not begin to effect the performance of the ecosystem (16:115). Gutierrez and Fey developed their model to simulate succession over a period of about 60 years. In keeping with the format of the original model, that same time frame is adhered to in WETM. Again, this simple assumption is a very important component of the entire process and the effects of feedback loops should be a focus of further study in the development of this model.

Water Level

The level of water in the wetland has a direct effect on the ability of obligate plants to grow. Jorgensen and Mitsch, in their studies found that an increase in precipitation resulted in an increase in growth. This implies that the water level of the system exerts some influence on the growth rate. They further state that if the water level was sufficiently high enough to inhibit gas exchange, a negative correlation would exist (14:317). Thus, there is an optimum depth of water associated with species growth. If

the water is below optimum, it will be held in the soil at high tension, limiting its uptake. If it were above the optimum, it would reduce the gas exchange within the root zone, thus limiting the growth. Jorgensen and Mitsch developed a simple model of the relationship between growth and depth to water table such that if the depth were within 1 meter of the optimum, growth would be reduced by five percent. The model is described as

$$H = 1 - 0.05(T-W)^2$$

where H = growth multiplier for water-table effects
T = actual depth to the unconfined water table
W = optimum depth for a given species.

The optimum depth of the unconfined water table varies depending on the species.

The range of depths normalized against ground surface is a variable which must be researched to further refine the operation of this model. The literature shows a generic value of -0.5 m as the optimum depth of several species, with some forested wetlands having optimums at -1.5 m (21:18). For the purposes of this study, -0.5 m will be taken as a starting point. While these are the actual values of the water depths, a constant, 2, is added to the actual depths to insure positive values during the operation of the model. The optimum water level (WL) is associated with the delay time for plants to absorb nutrients, or the nutrient absorption delay (NAD). As the water level changes, so too does the ability to absorb the nutrients. This is accounted for in the relationship of WL to NAD. Figure 4-3 shows how NAD varies with WL utilizing the above formula. The water level also affects the rate at which the organic nutrients are decomposed. The decomposition delay (DD) is directly affected by the anaerobic or aerobic conditions of the system. Figure 4-4 shows the relationship between WL and DD. As the level of water falls or rises, the value of DD is adjusted accordingly.

The average flow rate (AFR) of water into the system affects the nutrient import (NI)

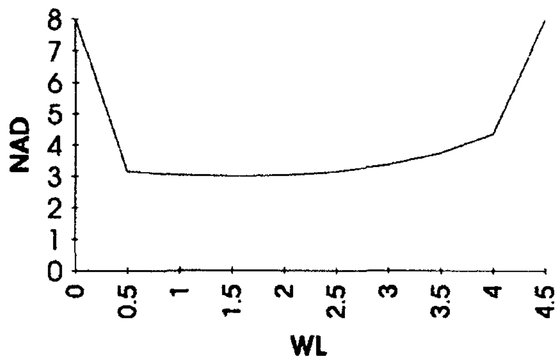


Figure 4-3. Nutrient absorption delay (NAD) as a function of water level (WL).

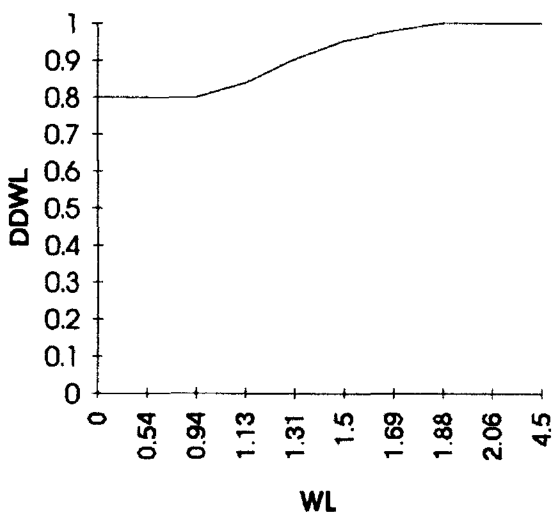


Figure 4-4. Decomposition delay decrease (DDWL) as a function of varying water level.

and export (NE) as well as the hydrology to species multiplier (HSM). These four parameters and their influences on the model are discussed in the following section.

Parameter Changes

To accurately track each step of the model and the changes from the original to the wetland representation, the level of plant biomass production and the variables associated with it will be discussed first, with all the other variables being altered as they are encountered with respect to this production level.

Plant Biomass

Plant biomass accumulates on the soil as a standing crop and is given by the equation

$$P = P + (dt)(PGR - PDR),$$

where, P = plant biomass

PGR = plant growth rate

PDR = plant death rate

The PGR is the sum total of new plant growth rate, NPGR, and replacement plant growth rate, RPGR. RPGR is a function of the nutrient limiting, NRPGR and the energy limiting, ERPGR, replacement plant growth rates.

Nutrient limiting replacement Plant Growth Rate

It is the NRPGR value which is affected by the water level. The growth rate multiplier due to water table depth is employed in this equation, as shown,

$$NRPGR = N/(NPRC)(NAD)$$

where N = nutrients available

NPRC = nutrient-to-plant requirement coefficient
NAD = nutrient absorption delay (a tabular function shown in figure 4-3).

The equation, N/NAD gives the nutrient availability rate, with NPRC converting the grams of nutrients to grams of plant biomass. Both the values of these parameters must reflect that of a wetland system. Estimated primary production for a typical wetland is averaged using data from several types of wetlands and is represented as 1250 g m^{-2} yr^{-1}, the standing crop of the mature ecosystem from which other parameters are derived (15:48).

The peak nutrient standing stock for a mature wetland is derived from studies presented by Prentki, Gustafson and Adams. Their study shows that the peak nutrient standing stock of nitrogen in several wetlands is approximately 41 g/m^2, which represents 1.9 % of the dry weight concentration of the biomass (20:173). Using these figures, the conversion factor NPRC is found by dividing the nutrient stock by the primary production biomass, which yields a value of $0.0155 g_n/g_p$. For a wetland ecosystem this figure makes sense, as the nutrients are used in a more efficient manner which would account for higher productivity.

GRASSM merely used the steady state figures of its ecosystem to determine these values. The literature does not specifically address the question of whether or not if the nutrient requirement for biomass changes from species to species in any of its research objectives. Therefore, the nutrient to biomass requirement value requires further study. It is believed that each species requirement for nutrients is unique, although it may be similar to other species. This is supported by the Prentki, Gustafson and Adams studies. They measured the nutrients associated with several species in different wetland areas.

While the results were similar, each species did have a different percentage of nutrients with respect to the dry weight of the biomass measured.

Gutierrez and Fey offer no insight as to how this parameter may change. Indeed, in their generalization of the model, they compilied a table depicting how the parameters would change from ecosystem to ecosystem. Their findings indicate an unknown change for this parameter. However, Mitsch points out that the above ground stock of nutrients in plants can vary wildly (3:363). Therefore, both values will be tested in chapter five.

NAD represents a nutrient absorption delay and was arbitrarily assigned a value of three months. Wetland literature on this type of absorption delay is sparse as well, although some generalization can be made. The growing season of a wetland is approximately 200 days or about six months. A graph of nutrient percentage in the standing stock plotted against the growing season shows that 50 % of the total concentration of nutrients occurs at a time associated with an elapse of 50% of the growing season (20:203). Using this information, it is not unrealistic to assume a 3 month delay in the absorption of nutrients into the standing biomass. This value occurs when the water is at its optimum level. The value will vary as the water rises or falls as shown in figure 4-3. Therefore the wetland equivalent of NRPGR is

$$\mathrm{NRPGR} = \mathrm{N}/(\mathrm{NPRC})(\mathrm{NAD})$$

with,

$$\mathrm{NPRC} = 0.0155 g_n/g_p$$

$$\mathrm{NAD} = 3 \text{ months (at optimum water level).}$$

Energy Limiting Replacement Plant Growth Rate

ERPGR has the value of the minimum of either the indicated replacement plant growth rate, IRPGR, or the energetically possible plant growth rate, EPPGR. IRPGR is

an exponential smoothing of a function in which material matures and decays according to its life cycle. Chamie and Richardson detail conditions in which the wetland system releases most of the organic soluble material within 12 months (24:116). Bernard and Gorham studied time life histories of selected wetland species and found that life spans are closely associated with the growing season. Their data reveal a life average of nine months for some species while others survive upwards of 14 plus months (15:40). The average of these species was approximately 11.5 months. Using this information, a plant decay delay, PDD, which is the average half life of the plants, takes on a value of 6 months.

Since IRPGR is simply a value of the natural plant decay rate delayed to account for the annual cycle of plant growth, NPDR must be smoothed by the suggested replacement cycle of the wetland plants, PDRSD. Therefore,

IRPGR = IRPGR + (dt)(1/PDRSD)(NPDR-IRPGR),

where, the initial value of IRPGR = P/PDD
PDD = 6 months
PDRSD = 12 months
NPDR = P/PDD
PDRSD = Plant depletion rate smoothing delay
NPDR = Natural plant decay rate

EPPGR is a function of both plant growth from photosynthesis, PPGRP, and energy storage reserves available, PPGRS. The energy storage reserves are termed plant vigor, PVV, or that excess energy stored as potential energy in various forms. This storage is available for a limited time period, after which, it dissipates in the performance of other quality functions or becomes fossilized. The value of this dissipation delay is 12 months and will remain unchanged for this model.

Gutierrez and Fey also assign an arbitrary value of one to the energy-to-plant requirement coefficient, EPRC. They claim this value to be chosen to ensure a

nonlimiting availability of energy. They further stipulate that changes due to the influences of allogenic factors or terrestrial biomes should influence this value. However, Boyd has found that the energy content of an average of 36 species of aquatic plants was approximately 15 kj/g (E:165). Using the appropriate conversion factors, this represents a value of 0.24 cal/g. Therefore WETM will use this value for its EPRC parameter.

The energy available for growth rate, EAR (cal-m^{-2}/month) is a function of the energy fixation rate, EFR, of plants and the plant maintenance coefficient, PMC. Again, the authors arbitrarily assigned values to these parameters to insure a nonlimiting availability of energy. The literature suggests that there is enormous difficulty in calculating energy budgets from the information now available. However, it does give some values of plant maintenance and gross production energy requirements. Mitsch presents the data in table 4-3 which suggests a range of values for gross production, maintenance and net primary productivity in terms of kcal m^{-2} yr^{-1} for both vegetation and consumers (3:359).

Mitsch continues to explain that a typical wetland yielding 2500 g m^{-2} yr^{-1} of net primary biomass has an energetic equivalent of 10,000 kcal m^{-2} yr^{-1}. Using this information, a value of 1250 g m^{-2} net primary production yields an energetic equivalent of 5000 kcal m^{-2} yr^{-1}. From this information, the gross production energetic equivalent of this system yields an energy fixation rate of 12,375 kcal m^{-2} yr^{-1}. This leads to a utilization rate for plant maintenance equal to 7,375 kcal m^{-2} yr^{-1}. Converting the units to accommodate the model (conversion equations are in appendix C) yields the following parameter value:

$$PMC = 0.49 \text{ cal } g^{-1}/\text{month}$$

where PMC is the plant maintenance coefficient, that energy required to maintain one gram of plant biomass per month. Gutierrez and Fey assumed an arbitrary energy fixation rate, EFR, double that of the energy to plant requirement coefficient. In keeping with

their model, that value will remain the same, or, EFR is 2 cal g^{-1}/month.

	kcal m^{-2} yr^{-1}
Producers	
Gross Production	4,500 - 27,000
Respiration	2,900 - 11,000
Net Production	1,600 - 16,000
Consumers	
Decomposers (bacteria & fungi)	1760
Decomposers (small invertebrates)	300
Mammal Consumption	232
Bird Consumption	20

Table 4-3. Wetland energy budget (3:358).

With values of PMC and EFR defined, it is now possible to calculate the energy rate required for plant maintenance, ERRPM and the energy availability rate, EAR. ERRPM is simply the standing crop P multiplied by PMC while EAR is the standing crop P multiplied by the EFR. Now it is possible to formulate the equations which define EPPGR.

$$EPPGR = PPGRS + PPGRP$$
$$PPGRS = PVV/ (EPRC)(PVDD)$$
$$PPGRP = EGAR/EPRC$$
$$EGAR = EAR - ERRPM$$

This closes out the equations required to find the value of replacement plant growth rate.

New Plant Growth Rate

The new plant growth rate, NPGR is a very involved parameter, requiring inputs from all aspects of the model. NPGR is represented as the minimum of either nutrient

limiting new plant growth rate, NNPGR, or the net new plant growth rate, NNPPR. NNPGR is nothing more than a function of the remaining nutrient availability rate, RNAR, where RNAR is the difference between NRPGR and ERPGR, both previously defined. NNPPR is quite complex. First, it is expressed as a function of the plant production efficiency factor, PPEF, and the gross new plant growth rate, GNPGR, where

$$NNPPR = (PPEF)(GNPGR)$$

PPEF is a function of species diversity and will be discussed later.

GNPGR is the minimum of that growth which is energetically possible, ENPGR, and that which is indicated by the availability of physical space in which to grow, INPGR. The ENPGR is a nonnegative value maximized by the remaining energy for growth availability rate, REGAR, where

$$REGAR = EPPGR - IRPGR,$$

both of which were defined earlier.

The indicated availability of space in which to grow requires further definition. Soil availability is measured as the ratio of the standing crop over the soil carrying capacity, called the soil availability index, SAX. This represents the degree of soil saturation and therefore the potential for new growth to occur. The authors of GRASSM give three alternative curves which indicate the plant growth rate with respect to the soil availability. The wetland literature is very sparse on this phenomenon, therefore the value of the plant production multiplier, PPM, is taken from the information provided by Gutierrez and Fey.

In referring to the table of alternative values for parameters based on different terrestrial systems, Gutierrez and Fey suggest that as the moisture of the system is increased, so too should the rate at which production occurs (9:212). This, coupled with the fact that wetlands on the whole are very productive ecosystems, suggest the shape of the curve depicting PPM should favor high production capacity when space for production is available. This leads to utilization of the largest valued curve hypothesized.

This reasoning is further supported by the growth rates of new shoots within a particular wetland region.

Bernard and Gorham recorded very quick emergence rates for new shoots at the beginning of the growing season, and very little new growth towards the end (15:46). Thus the values of PPM with respect to soil availability are shown in figure 4-5. Once these values were determined the total indicated new plant growth rate was calculated. The intensity of the new growth is proportional to the amount of plants already in the system. However, this growth is not instantaneous. Bernard and Gorham's data on new shoot emergence suggest a five month elapse from the start of the growing season to the time of appearance of the development of new shoots from the established root systems (15:46). Therefore the equation representing INPGR must be smoothed by that time period:

$$INPGR = INPGR + (dt)(1/INGAD)(NPPR - INPGR)$$

where, INGAD = 5 months (new growth delay value)
NPPR = (P)(PPM) (the production capacity for new plant growth rate)

Plant Depletion Rate

The above process accounts for the plant growth rate of the producers biomass stock. The rate at which the plants are depleted must now be accounted for. This depletion rate, PDR, is a function of the natural plant decay rate, which was defined earlier, and the grazing plant depletion rate, GPDR. The GPDR depends on the density and growth rates of the natural consumers, NC, which eat away at the plants. Focusing on the NC, its relative definition must be made clear.

GRASSM lumps together all kinds of consumers, both primary and secondary. This grouping of all consumers together was done by intent because the purpose of the model

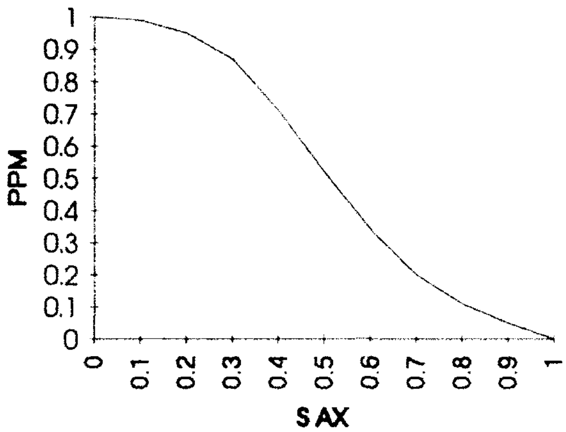


Figure 4-5. Plant Production Multiplier

is to account for the successional dynamics, not the specific dynamic process accounting for energy levels and transfer through each trophic level. Therefore, the values depicting the wetland function will also follow the same logic. However, there is limited information available on the amount of biomass of consumers in wetlands. This may be due to the population fluctuation of migratory animals or transits through the system which may depend on the habitat for food or refuge on a limited basis. There is a study which tries to quantify the amount of biomass in a wetland swamp system. For lack of additional information, this data will be used to formulate the amount of biomass associated with consumers.

The study performed by Mitsch states that the gross consumption rate for consumers is 252 kcal/m^2 (refer to table 4-3). This is converted into a value of biomass using the same procedure as discussed earlier (refer to appendix C) and yields a level of 63 g/m^2 for a mature system. With this information, NC can be calculated as

$$NC = NC + (dt)(NCGR - NCDR)$$

where $NCGR$ = natural consumer growth rate

$NCDR$ = natural consumer depletion rate.

These growth and death rates are the key to determining the total amount of consumers at any time within the system. The level of NC grows and declines in response with the availability of grasses. To understand this, the availability of food must be indexed (PAX), as

$$PAX = P/(PNCRC)(NC)$$

where PNCRC is the plants to natural consumers requirement coefficient. PNCRC is found by taking the steady state plant biomass, P, and dividing it by the steady state natural consumers biomass, NC. These values are determined to be 1250 g/m^2 and 63 g/m^2 respectively, which yields a PNCRC value of
19.84 g_p/g_{nc}.

Substitution of this value into the equation allows numerical computation of PAX. Gutierrez and Fey use an elaborate procedure for the development of consumers growth and death rates as a function of PAX. All of their assumptions deal with death and reproductive rates of animals with respect to the availability of food. These procedures are detailed extensively in their book Ecosystem Succession and are thought to be fairly constant in application throughout the ecosystems with slight alterations to the shape of the curves depicting mortality and reproduction relationships (9:102). In response to these changes, Gutierrez and Fey suggest the use of higher values for the more productive ecosystems. However, the literature located no information on mortality and reproduction rates for wetland fauna. In lieu of arbitrarily reshaping these curves at slightly higher values, the original data presented in the GRASSM model is utilized in this study.

Having done this, GPDR is calculated using the information on natural consumers,

$$GPDR = (NC)(NCRRS)(NCPRC)$$

where NCRRS is the natural consumers reproduction rate smoothed and NCPRC is the natural consumers plant requirement coefficient and is a value set at 10 percent of PNCRC. This result is then used in developing the plant depletion rate of the total plant biomass.

Organic Decomposition

As the plants or animals die, dead organic material must be broken down to complete the cycling of nutrients back to soluble inorganic form. The rate of organic material coming into the system, ONBA, is dependent on the plant organics, PONBA, and consumer organics, CONBA, material becoming available such that

$$ONBA = PONBA + CONBA$$

$PONBA = (P)(NPRC)/PDD$, all defined earlier,

$$CONBA = (COMBA)(NCPRC)(NPRC)$$

$$COMBA = (NC)(NCMRS)$$

where COMBA is the amount of consumer organic material becoming available and is a function of the consumers mortality rate smoothed as discussed earlier.

As the total organics enter the system due to death of the plants and consumers, the rate at which they are broken down must be formulated as a third order delay. This type of delay calls for the inorganic by-product of the decomposition to become available only after a slow gradual buildup once an input change occurred. The following set of equations accounts for a third order delay of the physical flow of nutrients undergoing decomposition.

$$ON1 = ON1 + (dt)(ONBA - NBA1)$$

$ON1 = (P)(DD3N)(NPRC)/(PDD)$, initial value of ON1

$$DD3N = 26$$

$$ON2 = ON2 + (dt)(NBA1 - NBA2)$$

ON2 = ON1
NBA2 = ON2/DD3
ON3 = ON3 + (dt)(NBA2 - NBA)
ON3 = ON2
NBA = ON3/DD3

where ON1 = organic nutrients - stage one
NBA1 = nutrients becoming available - stage one
ON2 = organic nutrients - stage two
NBA2 = nutrients becoming available - stage two
ON3 = organic nutrients - stage three
NBA = nutrients becoming available
DD3N = decomposition delay three - normal
DD3 = decomposition delay three

The decomposition aspect in wetlands is very complicated. Gutierrez and Fey present a loop in GRASSM which accounts for the decay to be a function of the availability of decomposers and that level to be dependent on the amount of organic material which decomposed. For purposes of retaining the simplicity of the operation of WETM and to maintain the original structural context of GRASSM, the format will remain intact with only alterations in delay times and effects of water level imposed on the system.

The time delays in this series of equations are the normal decomposition delay and a delay computed on total availability of decomposers. The value of normal decomposition delay according to Gutierrez and Fey is 12 months. This must be converted to reflect that of a wetland. Chamie and Richardson performed studies which suggest the half life decay times of certain organic material (24:123). Using this information, the exponential decay time constant is calculated to be 2.18 years or approximately 26 months (refer to appendix C). This time constant is the wetland value of DD3N.

GRASSM assumes that for decomposition to be accomplished in a normal amount of time, the indicated level of decomposing, ID, is proportional to the total amount of organic nutrients, ON.

$$ID = ON/ONDRC$$

where ONDRC = organic nutrients decomposers requirement coefficient. This value is found by dividing the amount of nutrients in the steady state condition of the standing crop by the steady state level of the decomposers. The value of the nutrients is 112.39 g_n/m^2 as determined earlier. The amount of decomposers per square meter is determined by referring to table 4-3 and converting the energy requirements of decomposers to a decomposer mass. According to Mitsch, the decomposers energy budget for a mature system is 1060 kcal m^{-2} yr^{-1}. Again, using the simple ratio formula, this equates to 515 g_d m^{-2}. Therefore, the value of ONDRC is 0.218 g_n/g_d. The actual amount of decomposers, D, is assumed to react to a buildup of organic matter by growing to the indicated level or,

$$D = D + (dt)\ (1/DRD)\ (ID - D)$$

where DRD is the decomposer response delay. The time for decomposers to build once an increase in organic material becomes available is set a 3 months by GRASSM and assumed to be the same for this study. Now the relative availability of decomposers is a ratio of indicated level to the actual level or,

$$DAX = ID/D$$

where DAX = decomposers availability index.

The decomposition delay, DD, resulting from a given value of DAX is then formulated as:

$$DD = [DDMIN + DDS\ (DAX)]$$

where DDMIN = decomposition delay minimum.

DDS = decomposition delay slope

There is no apparent basis for developing DDMIN. Gutierrez and Fey simply assume a value of 1/2 the DD3N. Then, assuming that DAX is a monotonically increasing function of the decomposers availability, when its value is one the decomposition delay is its normal value of 26 months. With this linear relationship hypothesized, the slope of the relationship is determined by the following graph:

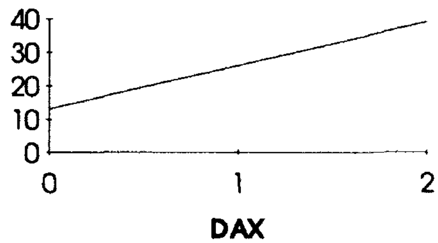


Figure 4-6. Decomposition delay as a function of available decomposers

Figure 4-6 determines the decomposition delay slope, DDS, which is (26-13)/1, or 13 months. This allows the value of DD3, the time constant of the third order exponential delay to be calculated as DD/3.

The decomposition of the organic material is assumed to occur under anaerobic conditions. During the course of succession, however, conditions in wetlands may change from anaerobic to aerobic. Chamie and Richardson indicate that the rate of organic decomposition increased 12-30% during drying and rewetting periods (24:116). Using this information and applying it to the model, an auxiliary variable, Decomposition to Depth of Water Level, DDWL, was constructed (refer to figure 4-4). This variable would decrease the DD value by an average of 20% during periods where the water level was below the ground surface. Therefore the value of DD is as follows:

$$DD = [DDMIN + DDS\ (DAX)]*DDWL.$$

Nutrients Cycling Loop

The only step left in this level is to close the nutrients cycling loop. This is simply found in GRASSM by the following:

N = N + (dt) (NBA - NDR)
where NDR = (NPRC) (RPGR + NPGR)
NDR = nutrients depletion rate.

However, GRASSM doesn't account for the flow of nutrients through the ecosystem. A wetland with a high rate of flow through it typically has a good supply of nutrients available for growth. However, this availability is limited to the surroundings of the wetland area. If surface runoff or ground water flow encountered conditions which allowed inorganic nutrients to be picked up in solution, the relative availability is good. Otherwise, the availability of nutrients is considered poor.

To account for the flow through of nutrients, WETM will have either good or poor nutrient availability in terms of g/m^2 influx to the system. Mitsch represents a good flux of nutrients into a system as 3.92 g/m^2, while a poor system has an influx of .343 g/m^2 (21:126). These figures are based on the measurement of water through the system. The flow through the wetland is estimated as a function of its water level. The equation which allows this is based on the measurement of water level above a control structure which then gives the flow in terms of meters (3:91). This implies that the surface area of the wetland must be known. Knowing the concentration of nutrients in the water allows the calculation of g/m^2 influx into the system. The influx is then assumed to be linerly distributed with the flow into the wetland. For example, at
0 m/yr, there is no influx of nutrients while at 20 m/yr there is an influx of 3.92 g/m^2. The poor nutrient loaded system has a linear distribution between 0 and 0.343 g/m^2.

WETM represents this as the auxiliary variables of average flow rate, AFR, nutrient import NI, and nutrient export, NE. However, it has been estimated that 20% of the

nutrients flowing into a system are actually detained in one form or another in the system (3:362). Therefore, the depletion rate of nutrients must be adjusted to accommodate the additional loss out of the system. These modifications to N and NDR are shown below:

N = N + dt (NBA + NI - NDR - NE)

where, NDR = (NPRC)(RPGR + NPGR)

NI = nutrient import, a function of AFR

NE = nutrient export, a function AFR

This completes the nutrient cycling loop which accounted for the affects of consumers, decomposers, and the flow of nutrients through the system, on the development of plant biomass in a wetland ecosystem.

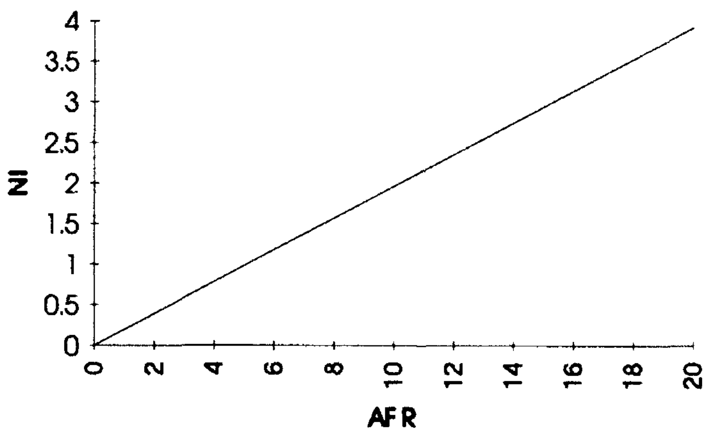


Figure 4-7. Nutrient import as a function of average flow rate.

Species Diversity

The last major compartment effecting the overall successional development of the wetland is species diversity. Hydrology plays a significant role in this section. Flooded waters provide a vehicle for the movement of materials, and it provides an elevation

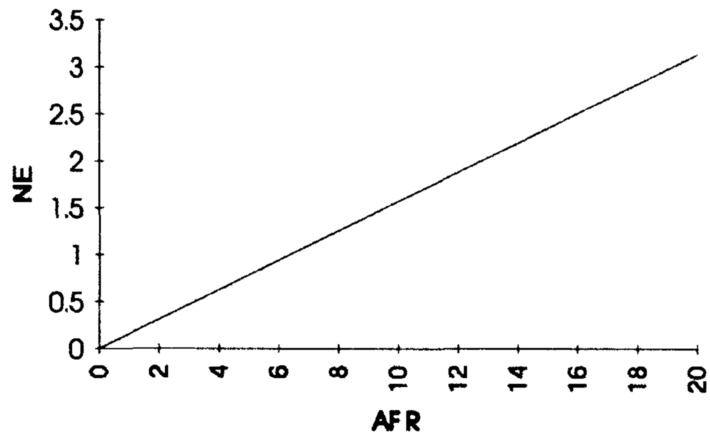


Figure 4-8. Nutrient export as a function of average flow rate.

change due to sedimentation of particulate matter in the water. Data exists which indicates plant species richness increases with increasing water velocity (17:66). Although the data doesn't give flow rates associated with the number of species, it does show how species diversity increases with flow characteristics of the system. The number of different species associated with the rates of flow are represented as the difference between those present in a good flowing system and those present in a poor stagnate system. While this doesn't indicate the total amount of species present, it can suggest a species diversity factor associated with flow through the system.

Mitsch suggests that a wetland is more productive when the system has a good flow rate through it while the productivity is very poor with stagnant flow (21:124). Using this hypothesis as an indicator of species diversity, a hydrology to species multiplier, HSM, is created. Assuming a good surface flow to be 20 m/yr (where the depth = vol/area of wetlands), the hydrology to species multiplier is 1. The value for a stagnate system of less than 2 m/yr is 0.23. Figure 4-9 shows the curve developed using information on species abundance under specific conditions from Gosselink and Turner (17:67). (See Appendix C for construction.)

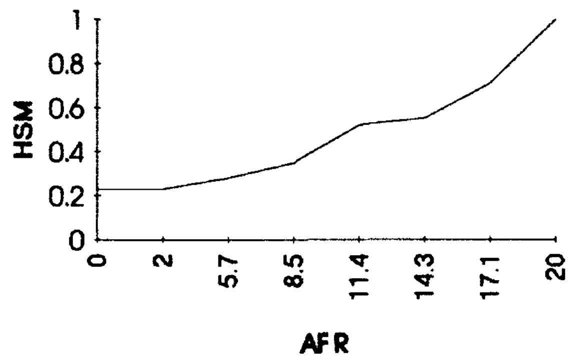


Figure 4-9. Hydrology to species multiplier as a function of average flow rate.

The data used to develop this was not obtained from studies that directly measured the species diversity as a function of water flow. Therefore, further research must be performed to verify the actual influences of hydrology to species diversity.

However, figure 4-9 represents a starting point for the affects on the species diversity increase rate. The amount of diversity depends on the rates at which species emerge and disappear. During succession, these rates are influenced by the total plant biomass accumulation, water flow, and soil capacity. For the most part, GRASSM accounts for the dynamic process of species diversity. The parameter values utilized are not easily found in the literature with respect to wetlands. Therefore, several of the parameters detailing species diversity will not be changed. However, there are some which will.

First, the diversity decrease rate has values for the species extinction rate multiplier, SMRM, a table which mirrors the values of PPM and thus will be changed to reflect the wetland values of PPM already discussed. To determine the overall species extinction rate, SMRM is multiplied by the normal species extinction rate SMRN. This value is represented as 0.01 by GRASSM. According to Gutierrez and Fey, this value should become smaller as the moisture of the systems goes up. However, there was nothing found in the literature that suggested a species extinction rate. There were references to

changes in species due to water level in the wetlands, but nothing quantitative (10:11). Therefore, WETM will assume the same value of SMRN at the optimum level of water in the wetland, but the value will increase by an average of 10% with the increase or decrease of water level (figure 4-9). This ties SMRN in as a function of water level. Therefore, diversity decrease rate, DDR, is formulated as:

$$DDR = (DIV)\,(SMR)$$
$$SMR = (SMRN)\,(SMRM)\,(SMWL)$$

where, DIV = Species diversity
SMR = Species extinction rate.
SMWL = Water influence on species mortality

Secondly, the species diversity increase rate, DIR, has a direct link to the rate of

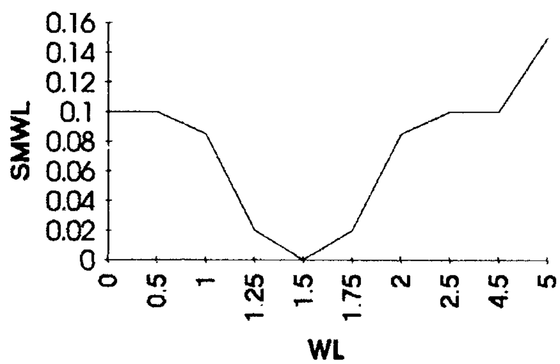


Figure 4-10. Percentage change of species mortality as a function of water level.

water flow into the system. The hydrology to species multiplier is incorporated into the equation via the species substitution rate, SSR and the species emergence rate, SER, as shown in figure 4-2. SSR is a function of the possible species substitution rate, PSSR, and the indicated species substitution rate, ISSR. The rate of the species substitution indicated is that necessary to replace species which have abandoned the ecosystem in the

recent past. This means that the indicated rate is equal to the value of the DDR after a substitution delay, SSD. GRASSM uses a value of 5 years for SSD.

Again, there is not much data available on the delay of one species substitution over another. Some literature suggests that the time of replacement is not that long (10:10). Therefore, this model will assume a SSD half the original value or 30 months. This logic also follows Gutierrez and Fey's assumption that the values of SSD get smaller in higher moisture content areas.

The ISSR also is dependent on the auxiliary variable HSM. As the flow into and out of the system changes, so too does the rate at which species emerge. This leads to the formulation of ISSR as:

$$ISSR = (1/SSD)\ (DDR - ISSR)\ (HSM)$$

The rate of the substitution actually possible, PSSR, however, is again a function of the availability of energy for diversification. This equation is similar to that of EPPGR. Here there is a energy to species requirement coefficient, ESRC, which has an arbitrary value of 1, and a diversity maintenance coefficient, DIVMC with an arbitrary value of 0.1. These are not supported by any literature available on grassland succession. Nor does there seem to be any information about these values in literature on wetlands. GRASSM established a value of 10 percent of the energy to plants requirement coefficient for DIVMC and arbitrarily assigned the value of 1 to ESRC. Utilizing the same methods, the WETM values will be 0.05 for DIVMC and 1 for ESRC.

With these figures we can find PSSR, a nonnegative value of the energy for diversification.

$$PSSR = MAX\ (0, EDAR)$$
$$EDAR = (1/ESRC)\ (REAR - ERRDM)$$
$$ERRDM = DIV\ (DIVMC)$$

This set of equations converts the energy availability rate remaining from growth to its equivalent in terms of further diversification potential.

SER, the species emergence rate, is a function of either the indicated species emergence rate, ISER, or the possible species emergence rate, PSER. PSER is the emergence rate which is still energetically possible after energy expenditures for diversity maintenance and species substitution are accounted for. Therefore, the remaining energy for diversified availability rate, REDAR is a function of PSSR and ISSR:

$$REDAR = PSSR - ISSR$$

which then yield

$$PSER = MAX\ (0, REDAR)$$

The indicated species emergence rate represents the appearance of additional new species brought about by the ongoing buildup of total biomass. Total biomass is a level adding plant, natural consumers and decomposers biomass together and accounting for a smoothing delay. This delay is set at 12 months, and nothing in the literature suggests a change to that value. At any given stage, the further accumulation of biomass in the ecosystem is indicative of increased species diversity in the near future. It also indicates previous increases in diversity that brought about the increased carrying capacity which in turn resulted in the present buildup of biomass (9:114). This describes a mutual causality of community growth and diversity.

First, the effects of growth on diversity are discussed. The level of species diversity is a function of the current accumulation of total biomass smoothed, BS. Gutierrez and Fey hypothesized that increments in species diversity is a nonlinear relationship with biomass ceasing to generate additional diversification after a certain point. This theory is assumed to hold true with wetlands as well. The values associated with this curve were arbitrarily assigned, however, the numerical values for the axis were not. The total biomass/m^2 is rounded and placed along the abscissa while the estimated total number of

species is placed along the ordinate. GRASSM had a total estimated number of species for its ecosystem as 200, representative of a mature system. The literature, although not explicitly calling for a total number of representative species in a wetland, does indicate that mature ecosystems are very diverse. For the purposes of this study, it is assumed that the number of species in a mature system is 1000. Therefore, the abscissa and ordinate will range from 0 to 1250 and 0 to 1000 respectively. Roughly the same shape curve as described in GRASSM will be employed in this model. Therefore, the value of indicated species diversity is a function of the total biomass smoothed.

$$IDIV = Table\ (BS)$$

At this point, the flow rate of water into the system has an impact on IDIV. Depending on the flow rate, the value of IDIV must be multiplied by HSM. this new value , indicated diversity due to hydrology, IDIVH is then used to determine the new species emergence rate, NESR. Because the emergence of species is not instantaneous, the rate must be smoothed over a period of time. GRASSM employs a species emergence delay, SED, represented as 12 months. This value is similar to the species substitution delay and the same logic used in decreasing its value is employed to SED. Hence, SED has a value of 6 months. Therefore, the new indicated species emergence rate is formulated as:

$$NSER = (1/SED)\ (IDIVH - DIV).$$

This depicts new species appearing in 6 months from the point where successional development has reached the stages appropriate for this emergence. However, diversification is gradual in nature, and there is a smoothing requirement of NSER to account for the time delay of diverse species emerging. This calls for ISER to be smoothed using an indicated species emergence adjustment delay ISEAD. This time constant was set at 5 years for GRASSM. Again, however, employing the same logic used in defining SSD, this value will be reduced 50% to 30 months. Now

$$ISER = ISER + (1/ISEAD)(NSER - ISER).$$

The last loop in species diversity is the influence of diversity on biomass. This section deals with the ability of the biomass to influence the development of soil carrying capacity, SCC. While there is extensive literature on wetland soils and their characteristics, there is virtually nothing found expressing a time for soil change to occur and how that change influences the amount of diversity of the system. This calls for the logic used in GRASSM to be carried over to WETM. The only changes to this is the amount g/m^2 the soil can support, ISCC, taken from a mature standing crop at 1250 g/m^2 and the adjustment delay, SCCAD, reduced to 30 months.

$$SCC = SCC + (dt)(1/SCCAD)(ISCC - SCC)$$

This completes the parameter changes to WETM and the justification of these changes. It should be noted that the values associated with this model are for a generic wetland. Its purpose is to show the expected health of a system by the amount of producer biomass standing during successional development. Managers will be able to adjust their site specific criteria to this model for an estimated ability of their sites to support a wetland ecosystem.

V. Model Testing, Results and Conclusions

Tests

The purpose of this study was to develop a model which accounted for the hydrological influences on wetland ecosystem succession. The original model presented by Gutierrez and Fey for the study of grassland ecosystem production was converted to a wetland model measuring the same production aspects of the ecosystem. The new model required additional auxiliary variables to define the existence of water in the system as well as changes to parameter values. These changes are summarized in tables 4-1 and 4-2.

Verification of the model is accomplished by running a series of tests which depict how the system operates under varying conditions. A series of eight simulations altering the values of water level and average flow rate will attempt to show how the productivity of an ecosystem will change under these external perturbations. Table 5-1 lists the parameter constraints. Each run is described in terms of what parameters are being tested, followed by a discussion of the graphical results and any conclusions which may be drawn. The variables of interest for each run are the total amount of respiration of the plants, RESP, the net primary production, P, the amount of organic nutrients produced by the system, ON, the amount of nutrients becoming available, N, and the gross plant growth rate, GPGR. These variables indicate the health of the ecosystem as it progresses through secondary succession. As the system develops under certain conditions, the success or failure of the ecosystem can be determined. This allows the manager to

develop and test plans under simulated conditions to alter, harvest or enhance the ecosystem.

The test conditions set forth in table 5-1 were selected for several reasons. First, test one simulates conditions as reflective of the original model, and the results from it should follow the pattern of GRASSM. Next, tests 2-5 and 7a-c show the affect of a high nutrient and low nutrient influx into the ecosystem, and the resulting development of that system. Tests 6a-c attempt to show how the system would react if the flow rates varied during the successional development and how, if any change is incurred due to this variation. Test 8a and 8b attempts to show the influence the actual water level has on the development of the system. Test nine depicts periodic flooding of the ecosystem and how

TEST	Water Level	Nutrients	AVG FLOW RATE
1	1.5 meters	High	0 m/yr
2	1.5 meters	High	5 m/yr
3	1.5 meters	High	10 m/yr
4	1.5 meters	High	15 m/yr
5	1.5 meters	High	20 m/yr
6a	1.5 meters	High	5 + fluctuation of (+/-) 15 m/yr every 2 yrs
6b	1.5 meters	High	20 + fluctuation of (+/-) 15 m/yr every 2 yrs
6c	1.5 meters	High	10 + varying fluctuation every 2 yrs
7a	1.5 meters	Low	5 m/yr
7b	1.5 meters	Low	10 m/yr
7c	1.5 meters	Low	20 m/yr
8a	1.5 - 2.5 meters	High	20 m/yr
8b	1.5 - neg 1.5 meters	High	5 m/yr
9	1.5 meters	High, pulsed	10 m/yr
10a	1.5 meters	High, NPRC = 0.03	20 m/yr
10b	1.5 meters	High, NPRC = 0.0155	20 m/yr

Table 5-1. Test constraints run on WETM variables.

the successional development is affect by the cleansing of the system of nutrients. Finally, test ten compares the development of the ecosystem under the influence of two different nutrient to plant requirement coefficients.

Overall, these tests are represented by parameter changes in the model. They accurately reflect the affects of hydrology on the system and the results will be able to help guide the managers to proper decisions involving the creation or enhancement of wetlands.

Test Case Number One

The first test will show the model under conditions which reflect only the changes made to the parameter values of the original model, meaning that the water level is at an optimum height and that the flow of water into the system is zero. This depicts a base level change from Gutierrez and Fey's model, with no influence from any of the wetland additional auxiliary variables, just changes made to the GRASSM constants and level values. This test is accomplished to show the validity of the parameter values and that the operation of the model is the same as the original. With this in mind, the same general shape of the curves shown in GRASSM (appendix A, fig A-2) should be observed in WETM.

By holding the water level at its optimum value, 1.5m, the parameter values associated with its operation are depicted as unaffected by the water level. This is because the original model assumed a constant supply of water, and no operation of the model is affected by its amount. Therefore, the optimum water level in WETM represents the water as a constant supply of the system, and the operation of the model is unaffected by its presence. The same basic premise holds true for the average flow rate. The original model had no external input of water to the system, therefore, by holding this

variable at zero, conditions reflecting the original test run of GRASSM are employed by WETM.

The results of this test, figure 5-1, depicts how the growth of the system proceeds through time. As the gross plant growth proceeds during the early months, net primary production remains very low. This is consistent with the new or young development of an ecosystem, as most of the energy utilized is for the establishment of the emerging and competing species.

As time progresses and the plants become established, the net primary production increases as more of the energy is used for growth and not the maintenance of the existing crop. However, as seen in the 130th month, the gross production and hence the net

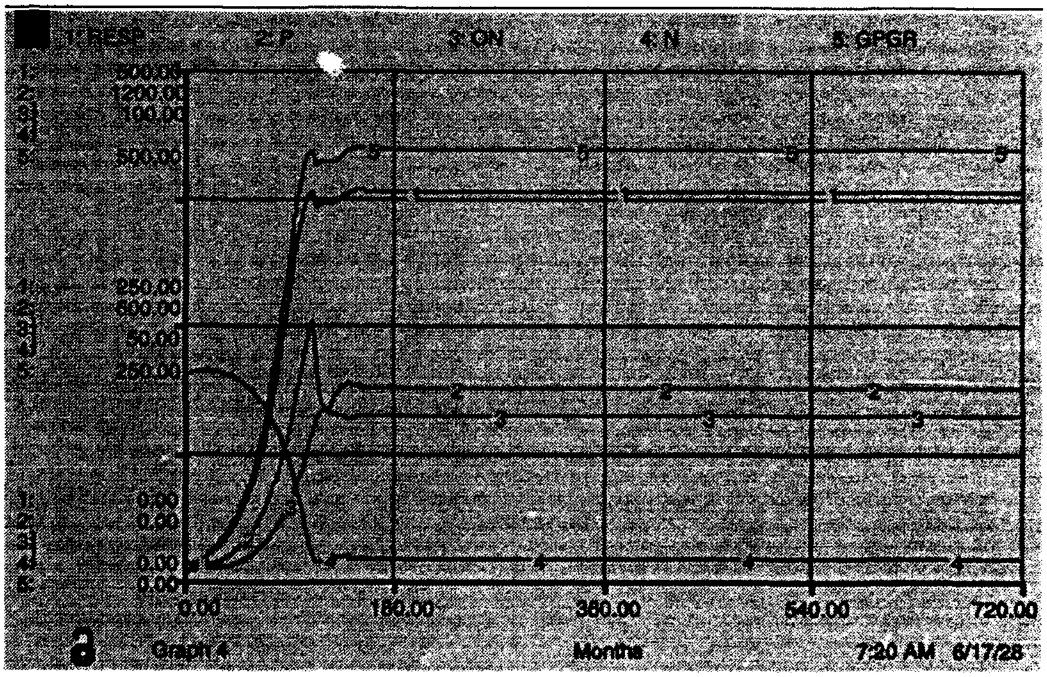


Figure 5-1. Test one, water level at optimum, 1.5 m, AFR = 0.

primary production peak, collapse and then level off at a constant value for the remainder of the study. This shows an over shoot and decline of the primary production, followed by its recovery. As the graph depicts, the soluble nutrients available are being consumed at a faster rate than the recycling rate of the required nutrients through the decomposition of the dead organic material. Thus the growth declined until the equilibrium point between the decomposition rate and that of the plant uptake rate was reached which then caused the system to remain constant over the duration of the test period.

This test can be correlated to that of a bog system in which no nutrients are imported into the ecosystem other than that available in precipitation. These systems are typically nutrient limiting and produce between 150-500 g m^{-2} yr^{-1} net primary production.

Test Case Two

This test allows for the import of nutrients into the ecosystem via surface or ground water flow. In this case also, the level of water is held constant. The rate of flow is 5 m/yr which imports approximately one gram per square meter and exports 0.8 grams per square meter. Even this small amount of nutrient influx drastically changes the growth patterns of the ecosystem. As figure 5-2 shows, the net primary production reached and surpassed its inflection point at which time other factors started to exert their influence upon the properties of growth rate within the ecosystem. However, before that occurs in its entirety, meaning that while the gross production rate of plant growth is still the principal reason for the rate of net primary production, the system starts to decline. This is due, once again, to the amount of nutrients in the system. As seen, the system recovers from its decline and again proceeds towards full maturity because of the constant inflow of nutrients, although it was somewhat delayed.

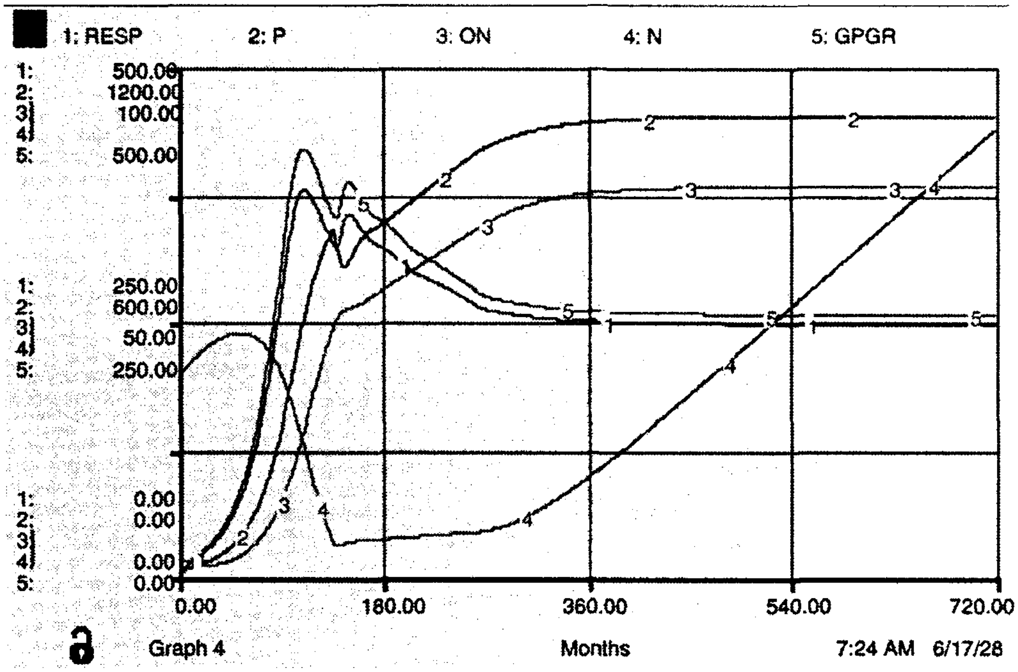


Figure 5-2. Test two, water level at optimum, AFR = 5 m/yr.

The sequence of events leading to this recovery is quite clear. At approximately the 100 month, gross production became limited. This was due to the soil carrying capacity of the system. As the soil became unable to support any more new life at that particular rate, it slowed as did the net primary production. However before the equilibrium between growth and soil capacity occurred, the nutrients became limiting. Before the collapse of the system occurred, the constant import of nutrients resupplied the system and allowed the growth to continue. Thus the secondary peaks in gross production.

During the second rise in the rates, one can see a slower rate of climb and decline of the net primary and gross production rates. This is because the nutrients are being utilized as soon as they are available in the system, where as before, the initial level and building of that level were able to supply an unlimited amount of the nutrients required. Now the nutrients are utilized as soon as they are imported. The import rate is less than the utilization rate until about the 340th month when the nutrients becoming available

through decomposition are enough to supply the gross production and net production rates. These rates level off at a constant value due again to the limited soil carrying capacity. Figure 5-2 shows a continual rise of the nutrients becoming available in the system. This makes sense and actually happens in nature. However, nature also accounts for periodic cleansing of the system by flood waters, droughts and so forth. This model does not account for the periodic loss of nutrients and thus they are always going to be depicted as continually rising. The accumulation of nutrients in the system is not a natural phenomena. There is always something which affects the system. It could be that the source of nutrients upstream is altered, or severe floods wash out all nutrients in the system. However, to depict these happenings requires further changes and additions to the parameters and variables which is outside the scopeof this work. The model concerns itself with the functional aspects of the ecosystem and as such, does not incorporate all possible scenarios occurring in nature. Rather, it depicts the behavioral patterns of growth and respiration throughout successional stages.

This is not to say that the model could not experience periodic flooding which would wash away the nutrients in the system. Test case 9 will explore that scenario.

Test Case Three

This test holds the water level constant and has a flow rate into the system at 10 m/yr. As seen in figure 5-3, the nutrients do not reach a limiting state. They are utilized and level off at about the 170th month and then begin to increase. This is because the constant inflow into the system is retained but not utilized as discussed in test number two. If the nutrient inflow were to stop after the 170 month, the level would reach an equilibrium for the remainder of the test period. The gross plant growth rate and the net

primary productivity are allowed to reach maturity without any disturbances from the lack of nutrients. This shows the classical successional pattern observed by Gutierrez and Fey in their Grassland Model. In comparing it to figure A-1, the shapes of the curves are very similar, suggesting that the development of the characteristics of the wetland follow that of an ecosystem proceeding through secondary succession.

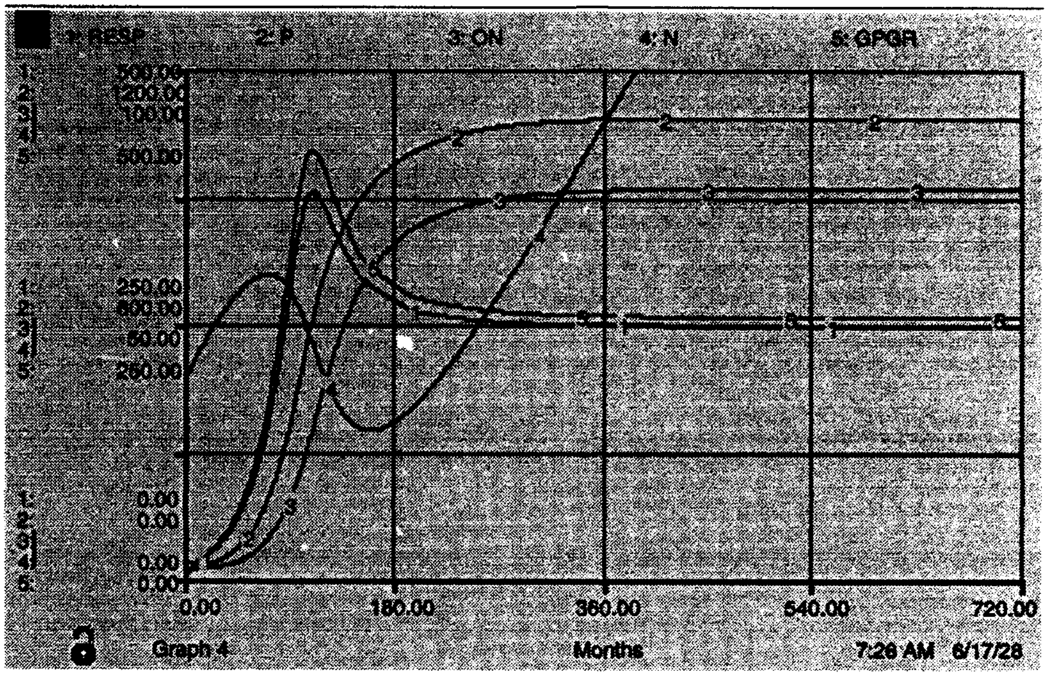


Figure 5-3. Test three, water level at optimum, AFR = 10m/yr

Test Case Four and Five

The test cases four and five display the same results, save the amount of nutrients flowing into the system. This shows that while the input of nutrients into the system is important for full development of plant biomass, there is a point when the nutrients no longer play any functional role. In other words, the system is limited by some other

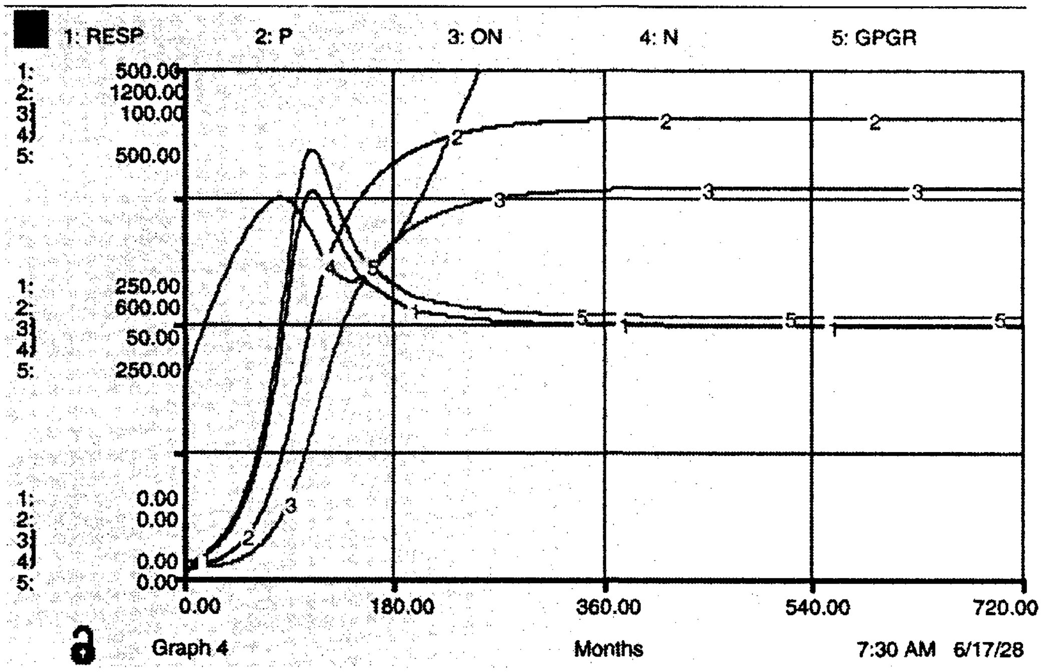


Figure 5-4. Test four, water level at optimum, AFR = 15 m/yr.

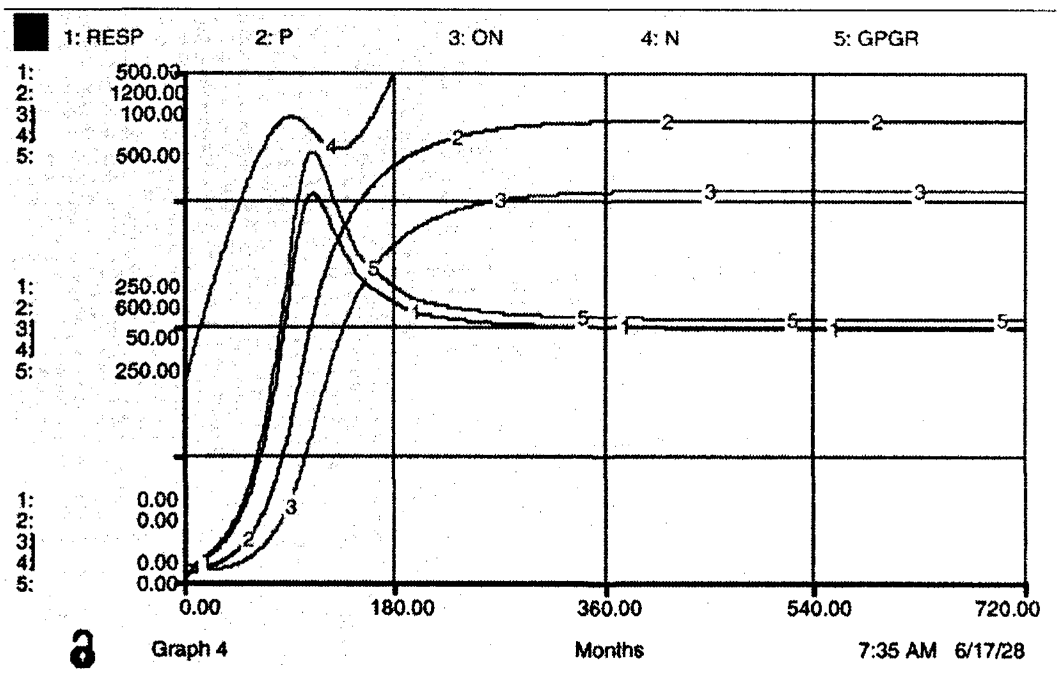


Figure 5-5. Test five, water level at optimum, AFR = 20 m/yr.

parameter and the uptake of nutrients is reduced based on that limitation. In this case it is the soil carrying capacity which slows and eventually limits the amount of biomass production. This limitation is observed in figures 5-4 and 5-5 at the apex of the respiration and gross plant growth rate. At about the 310th month the soil becomes completely saturated and the system only maintains the existing standing crop.

Test Case Six

This test case looks at the effects of a water system experiencing the periodic increase and decrease of the amount of water flowing into the system. Holding the water level at its optimum, 1.5 meters, the average flow rate was increased from an initial value of 5 m/yr by 15 m/yr at the 24 month mark and then decreased the same amount at the 48 month mark. This cycle continued throughout the 720th month. The system under a dry configuration, i.e. no AFR, displayed a mature value of approximately 500 g/m^2 of biomass production. The same system receiving the periodic water supply showed a drastic increase of production over the steady state case of 5 m/yr. As figure 5-6a shows, the periodic increase and decrease of flow rate into the wetland system allows the system to develop to full maturity as if it were seeing the a total affect of a 20 m/yr flow rate as shown in test number four. This shows that a system receiving periodic increases in flow rate is as productive as a system receiving a steady flow rate at above 10 m/yr.

This test was expanded to see what the reaction of the system would be if the initial flow rate was 20 m/yr and the rate was first decreased then increased every 24 months by 15 m/yr. As figure 5-6b shows, there is basically no difference in the production rate resulting from this scenario.

A third scenario was run where the flow rate was varied every 24 months (refer to

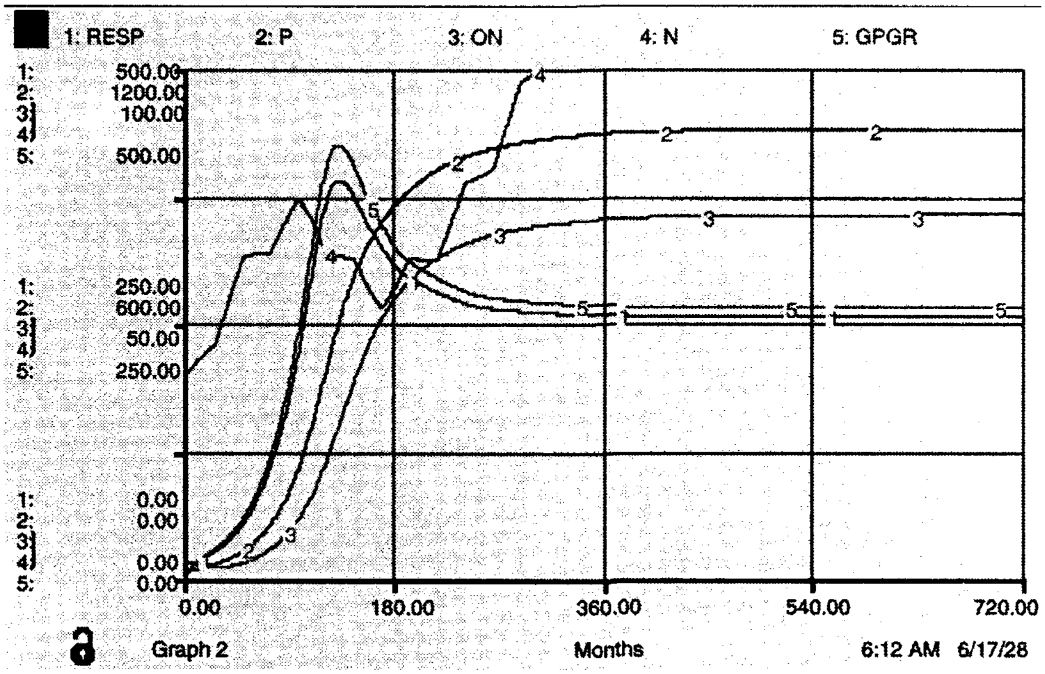


Figure 5-6a. Test six, WL at 1.5 m, AFR = 5 + step(15,24) + step(-15,48). . . + step(-15,720)

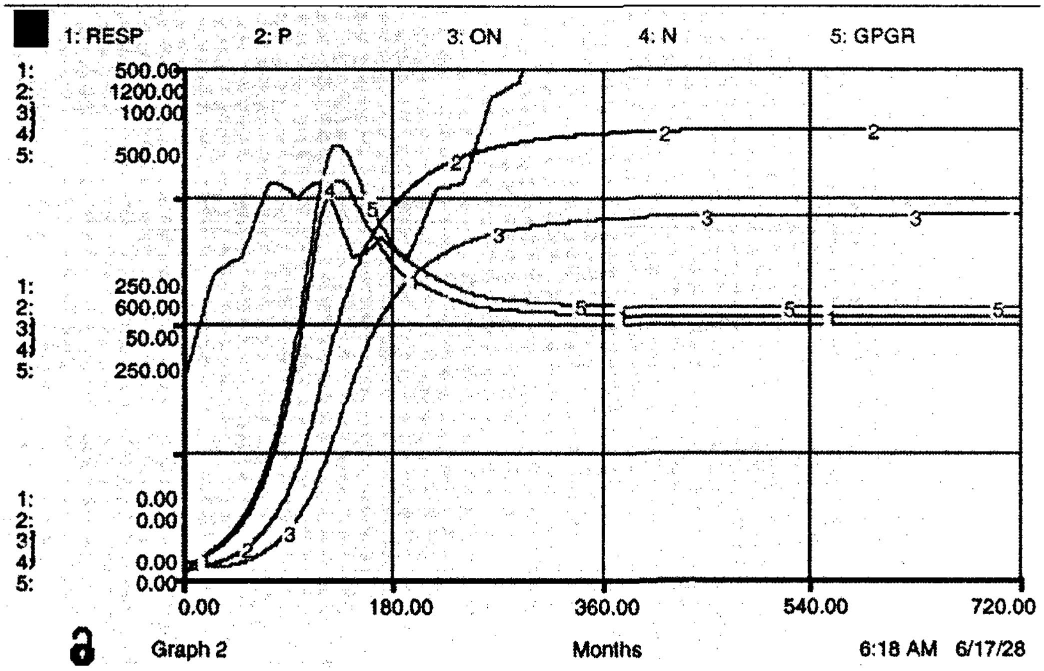


Figure 5-6b. Test six, water level at optimum, AFR = pulse (10,50,10).

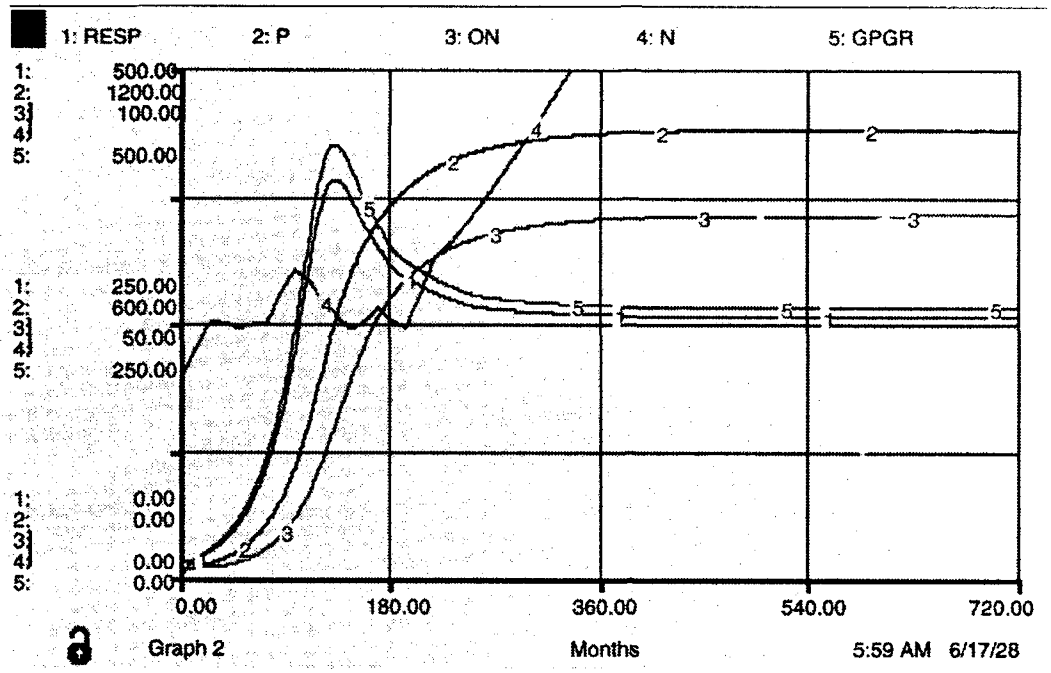


Figure 5-6c. Test Six, WL = 1.5, AFR varied between 0 and 20 m/yr.

table 5-1). The rate fluctuated between zero and 20 m/yr through the 200th month at which point it was a constant value of 10 m/yr. As shown in figure 5-6c, the net plant production was not hindered by the varying amount of flow rates in the system.

Test Case Six Supplementary

While running the tests concerning the average flow rate, another parameter, the hydrology to species multiplier, HSM, which is dependent on this rate and influences other parts of the model has not been discussed. While important to the rate of increase for species diversity, the diversity index and the new species emergence rate, its influence does nothing more than delay the system from reaching maturity by approximately 15

months. This suggests that on the successional scale, HSM is not that important and its influence on system behavior is negligible.

Test Case Seven

Tests two through six were run assuming that the flow of water through the system was highly loaded in nutrients. The next set of tests will compare the growth and net primary production of a system which receives less nutrient flux from the water flowing through the system. In test seven, the nutrient loading associated with the 5 m/yr flow is only 0.1965 g/m^2. As seen in figure 5-7a, the results are very similar to test one in which the nutrient loading was zero g/m^2. However, in this case the respiration and the gross production rates look as if they reached an equilibrium state. The fact that the net primary production is still increasing suggests that those values are not at equilibrium, rather they are slowly declining. This shows that given time, although we are are looking at approximately 300 years, the system under these conditions will reach its full maturity. Figures 5-7b and 5-7c show the same basic affect of the poor nutrient loaded system, although the time required for each to reach a mature state is decreased. Figure 5-7b has a influx of nutrients at 0.034 g/m^2 while figure 5-7c experiences an influx of 0.0686 g/m^2. Even at these small amounts, a wetland will develop and maintain itself if the conditions remain the same.

Test Case Eight

In this test, the average flow rate is held constant at 20 m/yr while the water level sees an increase of 2.5 meters at month ten. This has the effect of increasing the depth of

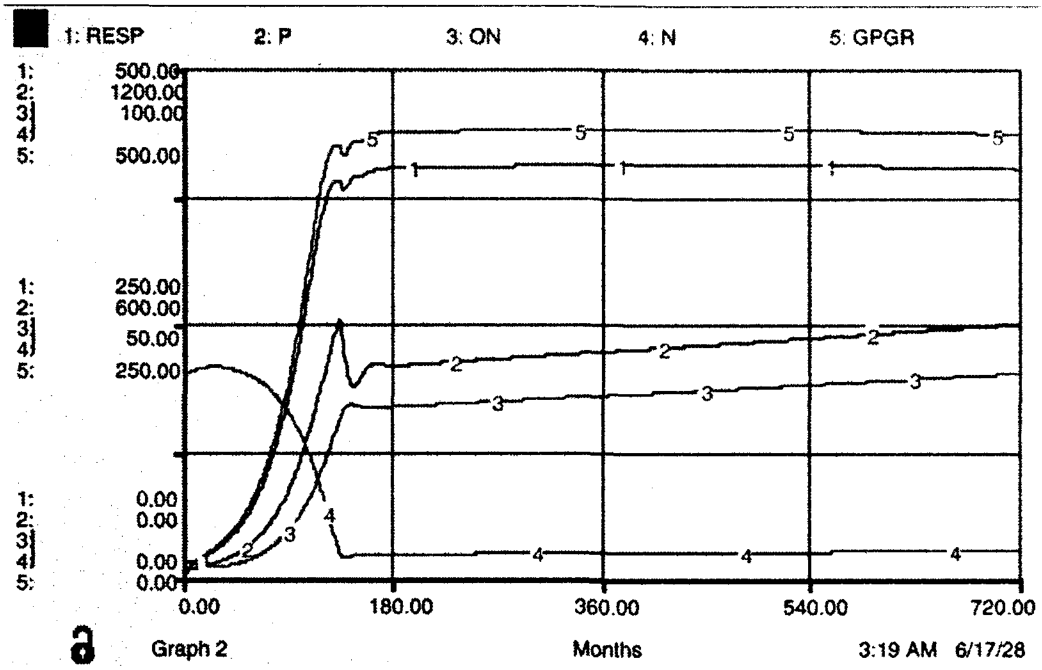


Figure 5-7a. WL = 1.5m, AFR = 5m, nutrient loading is low.

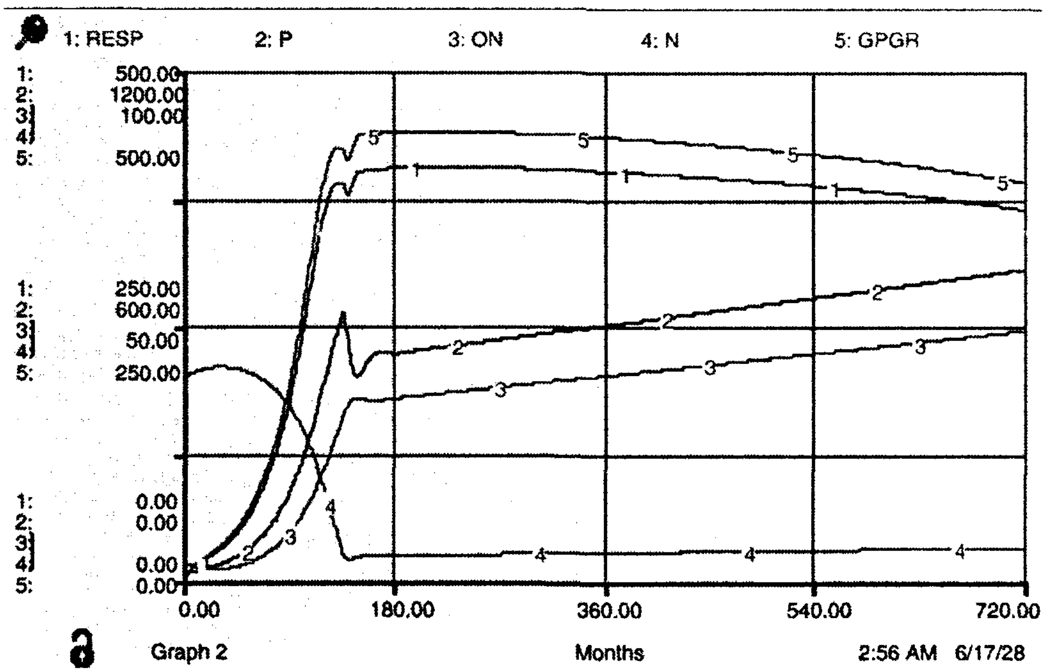


Figure 5-7b. WL = 1.5m, AFR = 10m/yr, low nutrient loading

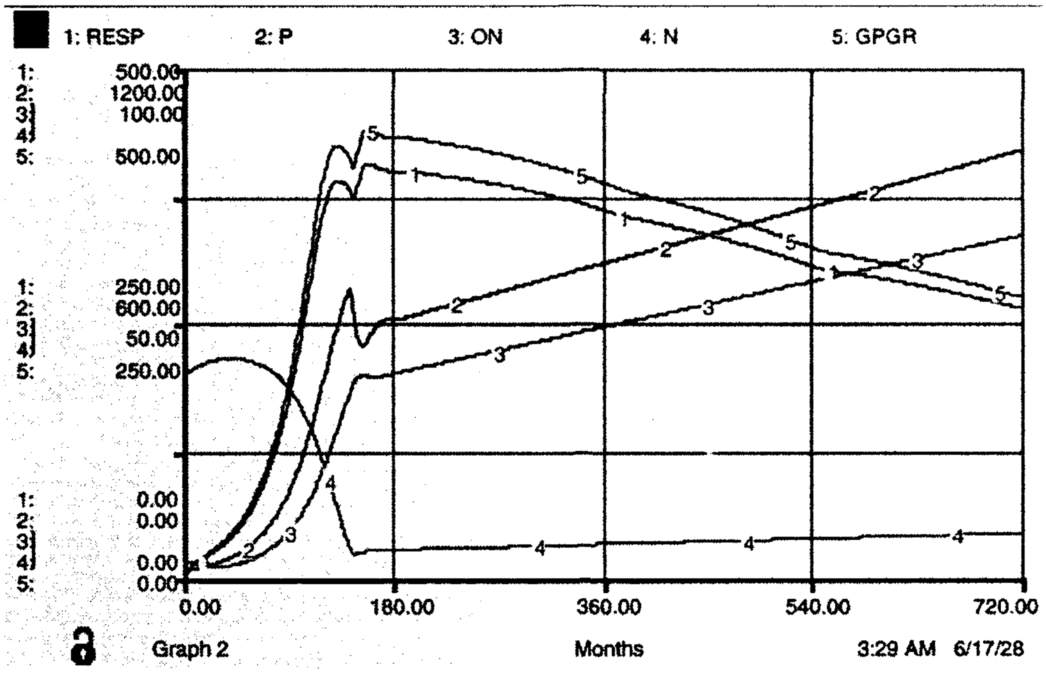


Figure 5-7c. WL = 1.5m, AFR = 20 m/yr, low nutrient loading.

water to the maximum level and still be considered a wetland. It also decreases the growth capability by approximately 20 percent as discussed in chapter four. Figure 5-8a shows the water level influencing no effect on the development of plant biomass. It was thought that the constant import of nutrients into the system may have caused this. It was theorized that the water level would decrease the rate of growth of the wetland plants. However, as figure 5-8a shows, that was not the case. Another test using the same parameters as test number 2 with an additive water level step function was again run. The results of this, figure 5-8b, also show no change in the amount of biomass produced. In fact, any amount of variation in the water level produced no impact on the production of biomass. While there was no effect on the end result, the water level did influence other areas. The total plant biomass was the same, however, it took approximately 20 months longer for the stock to achieve its maximum value. There was also a difference in the

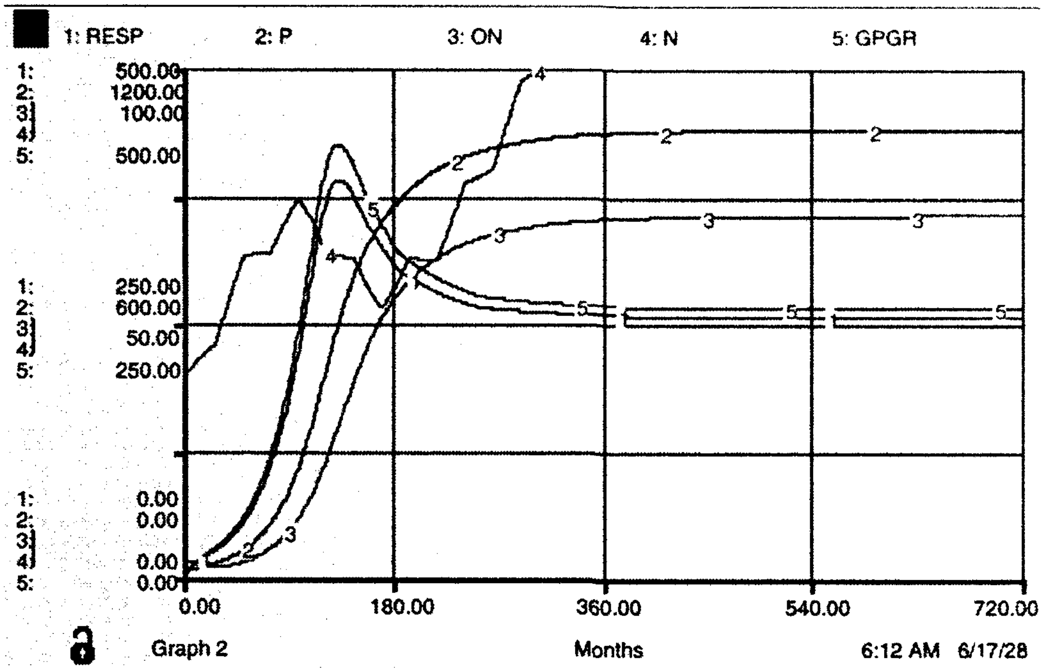


Figure 5-8a. Test eight, water level step function as an increase of 2.5m, AFR = 20 m/yr.

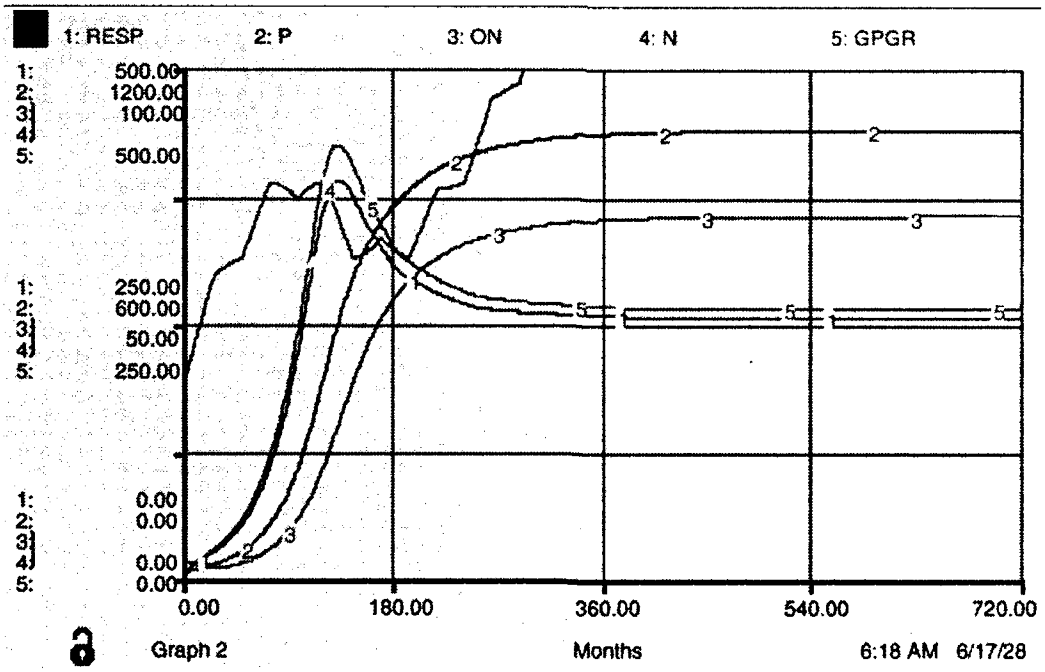


Figure 5-8b. Test eight, water level step function as a decrease of 1.5m, AFR = 5 m/yr.

amount of organic material remaining in the ecosystem. The maximum value of the mature system with an optimum water level was 71.14 g/m^2, while the lower water level system showed a value of 59.59 g/m^2. It also exerted an influence on the death rate of the many species of the system. The low water level proved to increase the death rate, although, the amount was very small. Finally, the water level has a direct effect on the nutrient limiting replacement plant growth rate. It decreases that value by approximately 60 percent. This is a significant decrease in the plants ability to grow, however, the model accounts for other factors which are more limiting than this observed decrease.

Test Case Nine

The explanation of the results from test case two describe the accumulation of the nutrients in the wetland during the life span of the ecosystem. The accumulation does occur in nature, however, there also exists circumstances which deprive the system of nutrients. The impact of nutrients being removed from the system under conditions other than ideal should be considered. To do this, several catastrophic floods will be imposed on the simulated wetland. First, the nutrient level will see a flood which removes 50 percent of the nutrients from the system every seven years, starting in year two, type A flood. Also, there will be a more severe flood which eliminates 80 percent of the nutrients from the system, starting in year 10 and occurring every 10 years, type B flood. The initial parameter values are that of test case five. Figure 5-9 shows the affect of these floods on the ecosystem. The affects of the first flood, type A, on the system are negligible. However, the second flood, type B, disrupts the cycle enough to cause the nutrients to become limiting. The system recovers due to the influx of nutrients under the normal conditions. The second and subsequent type A floods have no apparent affect on the net primary production. It is the type B floods which remove enough of the nutrients

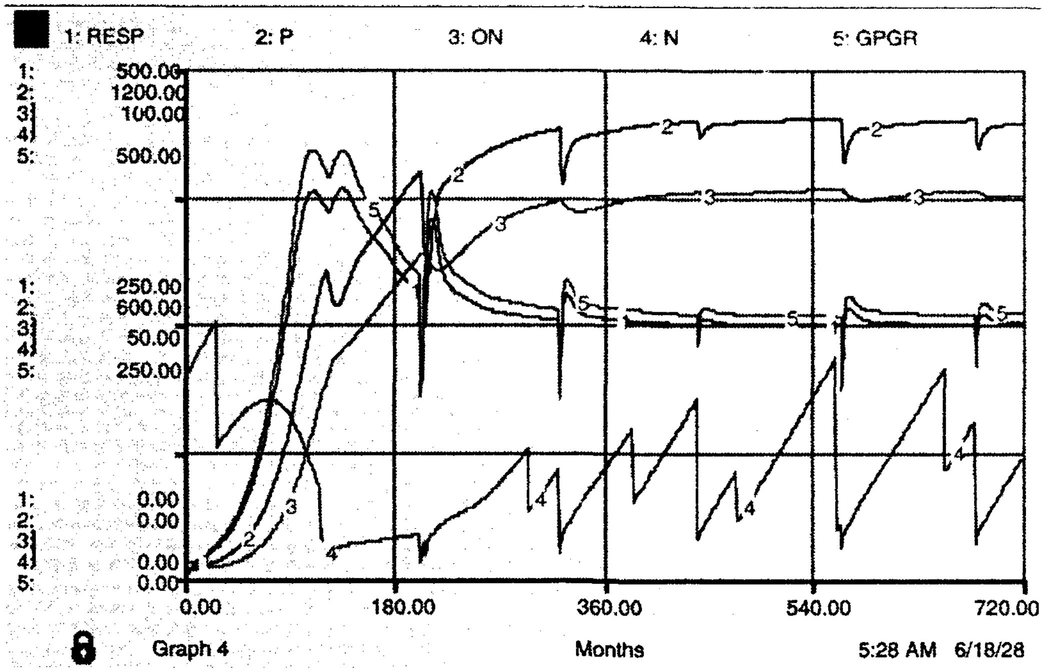


Figure 5-9. Effects of flooding on the nutrient level and subsequent system production.

to cause a reaction in the development patterns of the system. However, upon closer examination, the type B floods affects are also dependent on the amount of nutrients in the system. In the 440th month the level of nutrients in the system was almost enough that an 80 percent reduction had very little effect on the development pattern. If it was not for the 50 percent reduction of the type A floods, after a nominal time, the type B floods would also have a minimal if not any impact on the system. As is shown, the floods and subsequent loss of nutrients from the system does effect the growth patterns of the ecosystem. In fact, the flooding raises the level of primary production by 25 g/m^2 over the 720 month test.

Test Case Ten

As discussed in chapter four, Gutierrez and Fey used field data from their grassland study to determine the nutrient to plant requirement coefficient. They took the nutrients found in the standing stock of the grassland and divided it by the biomass found over the same area. This yielded a value of 0.03 grams nutrients to grams plant. This amount was not documented in any literature that was researched. They simply took the existing field data and utilized it in their study. As a follow up to GRASSM, they made several recommendations as to how, as different ecosystems are modeled, the parameter values would change. For each system they listed, this particular parameter was described as an unknown change. This implies that there was no information found on the amount of nutrients locked in the biomass compartments for different ecosystems. In researching the literature for this study, no data representing this type was found. Prentki, Gustafson and Adams did perform studies which measured the nutrients as a percentage of the dry weight of the biomass for different wetland species. As stated in chapter four, the average value of nutrients tied up in the biomass for similar species was used in determining the requirement coefficient. Test case ten examines the model with both values of the nutrient to plant requirement coefficient. Figure 5-10a shows how the system proceeds with the original coefficient from GRASSM. Figure 5-10b utilizes the data from the Prentki, Gustafson and Adams studies. The actual rate of net primary production does not change from one test to the other. However, the rate of utilization of the nutrients is greater for the original value. This makes sense as there is a requirement for more nutrients under one test than the other for each gram of plant produced. The other major difference between the two values is the amount of and rate of development of organic material. For the original value of NPRC, the organic nutrients produced rises off the scale very quickly. It reaches equilibrium at approximately 300 g/m^2. When the

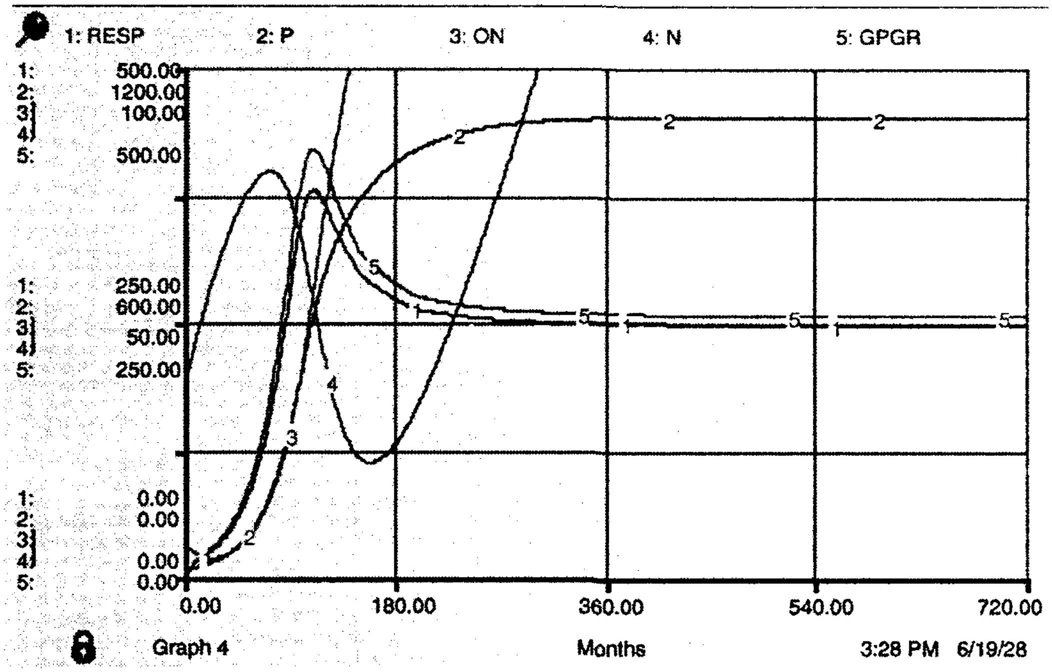


Figure 5-10a. Test ten, NPRC = $0.03g_n/g_p$.

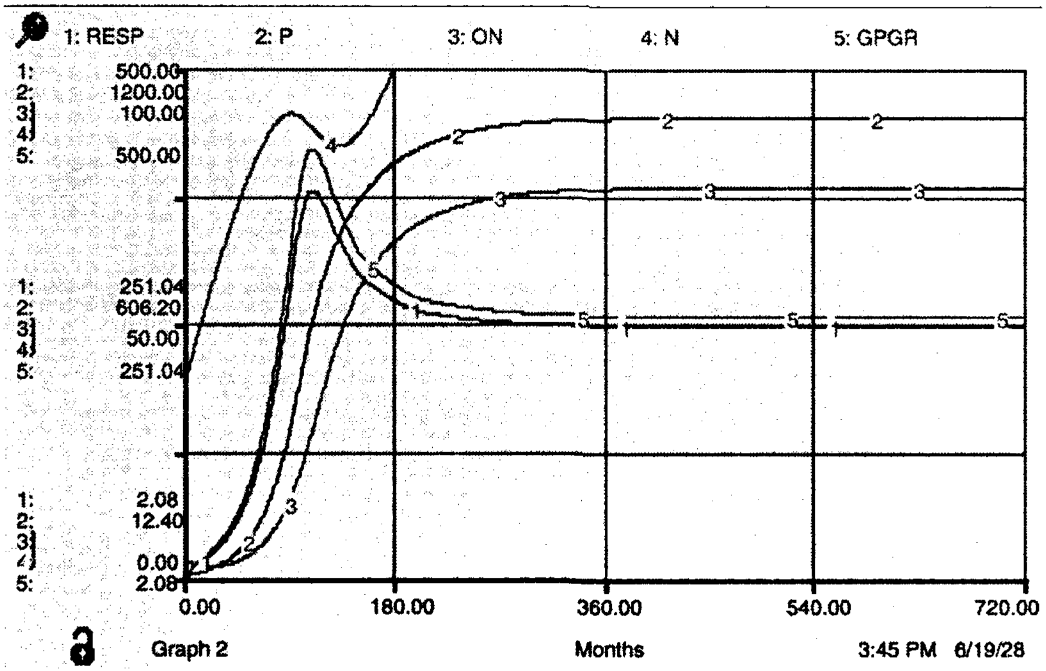


Figure 5-10b. Test 10, NPRC = $0.0155g_n/g_p$

value of NPRC is decreased to 0.0155, the rate of development of organic nutrients is much slower, and only reaches a value of approximately 75 g/m^2, a substantial difference. This shows that more nutrients are locked up in the biomass with the higher requirement coefficient than with the lower.

CONCLUSION

The purpose of this model was to observe the influences of hydrology on the succession of a wetland ecosystem. As the tests indicated, the influence was rather subtle to extremely important. First, the hydrology to species multiplier does not have a profound effect on the system. If this variable were omitted from the model, no change would result other than a decrease in the time required to reach maturity.

The water level was another variable that, up front showed no visible influence on the model results. However, it did affect the parameters associated with it to a large extent. It is simply the fact that other parameters dealing with the energy related aspects of the model are dominant over the nutrient parameters. The construction of the model was such that either the energy limiting or nutrient limiting factors controlled the amount of gross production in the system. The compilation of the mathematical equations, regardless of input of water level, still called for the energy limiting factors upon production to dominate. Other models depicting wetland development, such as those presented by Mitsch, Gosselink, Jorgensen and others only account for the affects of water or nutrients alone on the development of the system. The energy relationships are simplified, if not totally ignored, thus showing the water level to have a somewhat more profound effect on wetland development (21:129). The effects of the water level variation were discussed and if taken separately from this model, would have a significant

impact on the results. One possible explanation of the apparent influence in this model is that the species are generic, and that the growth of facultative plants in lieu of obligate would develop regardless of the amount of water present in the system.

The influence of the average flow rate into the system had a direct effect on the overall development of the system. The nutrients associated with the flow rates allowed the system to reach its maturity. In the test where there were no inflow of nutrients, the biomass peaked early and declined to a level which was reflective of a nutrient limited bog which depends solely on precipitation for its nutrient import. The nutrients in the system were recycled to provide the level of net primary production seen in the test. As the level of nutrients was increased, so too did the rate at which maturity was reached. After a point, however, the amount of nutrients entering the system no longer mattered. The wetland became saturated with nutrients to the point that other limiting factors inhibited their uptake.

It is also interesting to note the difference between the high nutrient influx vurse the low nutrient influx. In the high system, any flow rate into the wetland produced an eventual fully mature ecosystem easily within the time frame of the test. In the low nutrient loaded system, this was not the case. Regardless of the flow rate, the system came nowhere near reaching any semblance of climax. The best, at 20 m/yr AFR, showed that eventually, over a period of about 150 years, the system would have been fully mature. This happens assuming the conditions remain constant for the duration of the test, and that no other disturbances to the model take place. Conversely, as test nine shows, a high nutrient influx into the system provides a buffer and allows the ecosystem to proceed to its climax, although a small delay in the successional dynamics may occur. Even with the periodic removal of up to 80 percent of the nutrients in the system, primary production proceeds until other factors limit its growth.

Test ten detailed interesting results in terms of nutrient uptake and organic development. While the system will see no change in the amount of net primary productivity, under a high nutrient influx system, there is a drastic difference in the amount of organic material that is accumulated. This is probably accounted for due to the larger amount of nutrients locked in the biomass and the decomposition time associated with breaking down the organics. The higher percentage of nutrients in the biomass results in a longer decomposition time, thus more organic material is allowed to accumulate.

There was another section of the model which exerted its limiting abilities on the development of the system. This proved to be the development of the soil and its carrying capacity. As the soil became more saturated, the ability of the plants to generate new growth, other than that associated with replacement, became severely limited. This area needs more attention in terms of the soils ability to expand, develop and create more capacity in which the plant community can grow. There is also much work required in developing the influence of the soil on the water within the system. A direct feedback loop needs to be incorporated into the model accurately representing this condition.

RECOMMENDATIONS

Model Weaknesses

WETM is a variation of a grassland ecosystem model developed by Gutierrez and Fey. Their model contained several parameter constants associated with direct data from a mature grassland ecosystem. These constants were converted to represent mature ecosystems involving wetlands. For the most part, the information providing the changes was tied into a mature ecosystem which produced 1250 g m^{-2} yr^{-1}. However, the data

was not specifically developed for this type of study. The methods of collecting and interpreting the acquired information was done with respect to individual studies and the systematic approaches tied to them. In addition, several of the changed parameters utilized information acquired from individual studies not tied with the 1250 g m^{-2} yr^{-1} information, introducing even further suspect in the accuracy of the constant values. To assure that the values used in the development of this model are consistent, a full study of a mature wetland with the intent of gathering information for these parameters is required. However, even without this site specific data, the constructed model did display the characteristics of ecosystem successional development.

The main areas of concern are the soil carrying capacity, the nutrient and decomposer to plant requirement coefficients and the development of species diversity. Again, while the results of this study support the theoretical development process of an ecosystem, further refinement in these areas is required to substantiate the results. The area of soil carrying capacity is the largest unknown in the model. Information changing the values associated with this came from the methodologies employed by Gutierrez and Fey, not from the existing literature on wetlands.

The nutrient to plant requirement coefficient needs further definition. This uptake requirement should be studied with the specific intent of identifying the amount of nutrients associated with each type of wetland plant. This will allow the accurate representation of materials deposited and consumed under these conditions.

The other major weakness of the model is the lack of feedback loops of hydrology. Although it has been shown that some hydrological effects on wetlands take many years to develop, the overall effect should be incorporated to accurately account for all aspects of wetland development. Change to the structural components of this model were outside the scope of this research, therefore no feedback loops were incorporated.

These weaknesses of the model all are excellent areas in which to conduct further research. The development and clarification of these areas could greatly benefit the Air Force by allowing the complete development of a wetland ecosystem model.

Applications to the Air Force

The intent of this work was to construct a model which will aid the air force manager in determining what areas and consideration must be made to construct or enhance their wetland areas. The model is user friendly requiring only simple adjustments to the parameter values, shown in table 4-1. The substitution of site or species specific information will enable the manager to theoretically determine if the ecosystem they propose will be successful. A successful system is determined in terms of the ecosystem health. The parameters of the model which measure the health are the gross and net primary production variables. A wetland will have certain characteristics associated with it. If the manager wants a specific type of wetland developed, the amount of biomass produced in a similar wetland should be a known. By substituting the site specific data into the model, the relative health can then be determined.

With further development and account of hydrological effects on the model, it will be possible to classify wetlands by specific type. Categorization of the water levels can be tabulated along with the optimum parameter values as described in the model. The manager will then be able to select a particular ecosystem and import the data from the table to determine if a particular wetland type is capable of surviving and developing into a mature ecosystem.

As the model is constructed, the manager can take the criteria existing in their areas and import the specific data required to obtain a particular type of wetland. For example, if the nutrient to plant requirement values do fluctuate according to species, the formation

of peat or mineral wetlands can be determined simply by altering the type of species planted. The nutrient influx is another factor which the manager can input and determine what the production rates and amount of production will be. In other words, with some refinement, a schedule of parameter inputs can be developed to construct or enhance different classifications of wetlands.

Wetlands are an ever increasing area of concern for the general public, as well as the department of defense. Air Force environmental engineers must take an active role in preserving and developing wetland ecosystems along with the ability to fly and fight.

Appendix A: Verification of Grassland Ecosystem Succession Model

This Appendix contains the diagram and the computer code of the original converted grassland succession model.

The following is a list of equations adapted for STELLA to perform the operations of the GRASSM model.

```
BS(t) = BS(t - dt) + (BSR) * dt
INIT BS = P+D+NC

BSR = (1/BSD)*(P+NC+D-BS)
D(t) = D(t - dt) + (DR) * dt
INIT D = (ON1+ON2+ON3)/ONDRC

DR = (1/DRD)*(ID-D)
DIV(t) = DIV(t - dt) + (DIR - DDR) * dt
INIT DIV = 1

DIR = SER+SSR
DDR = DIV*SMR
INPGR(t) = INPGR(t - dt) + (INPGRR) * dt
INIT INPGR = 0

INPGRR = (1/INGAD)*(NPPR-INPGR)
IRPGR(t) = IRPGR(t - dt) + (IRPGRR) * dt
INIT IRPGR = P/PDD

IRPGRR = (1/PDRSD)*(NPDR-IRPGR)
ISER(t) = ISER(t - dt) + (ISERR) * dt
INIT ISER = 0

ISERR = (1/ISEAD)*(NSER-ISER)
ISSR(t) = ISSR(t - dt) + (ISSRR) * dt
INIT ISSR = DIV/SMRN

ISSRR = (1/SSD)*(DDR-ISSR)
N(t) = N(t - dt) + (NBA - NDR) * dt
INIT N = 14

NBA = ON3/DD3
NDR = NPRC*(NPGR+RPGR)
NC(t) = NC(t - dt) + (NCGR - NCDR) * dt
INIT NC = .00625

NCGR = NC*NCRRS
NCDR = NC*NCMRS
NCMRS(t) = NCMRS(t - dt) + (NCMRSR) * dt
INIT NCMRS = .074
```

NCMRSR = (1/NCRD)*(NCMR-NCMRS)
NCRRS(t) = NCRRS(t - dt) + (NCRRSR) * dt
INIT NCRRS = 0.096

NCRRSR = (1/NCRD)*(NCRR-NCRRS)
ON1(t) = ON1(t - dt) + (ONBA - NBA1) * dt
INIT ON1 = (P*DD3N*NPRC)/PDD

ONBA = CONBA+PONBA
NBA1 = ON1/DD3
ON2(t) = ON2(t - dt) + (NBA1 - NBA2) * dt
INIT ON2 = ON1

NBA1 = ON1/DD3
NBA2 = ON2/DD3
ON3(t) = ON3(t - dt) + (NBA2 - NBA) * dt
INIT ON3 = ON2

NBA2 = ON2/DD3
NBA = ON3/DD3
P(t) = P(t - dt) + (PGR - PDR) * dt
INIT P = 1

PGR = NPGR+RPGR
PDR = NPDR+GPDR
PVV(t) = PVV(t - dt) + (PVAR - PVDR) * dt
INIT PVV = 0

PVAR = MAX(0,EVAR)
PVDR = PVV/PVDD
SCC(t) = SCC(t - dt) + (SCCR) * dt
INIT SCC = SCCT

SCCR = (1/SCCAD)*(ISCC-SCC)
BSD = 12
COMBA = NC*NCMRS
CONBA = COMBA*NCPRC*NPRC
DAX = ID/D

DD = DDMIN+(DDS*DAX)
DD3 = DD/3
DD3N = 12
DDMIN = 6
DDS = 6

DIVMC = 0.1
DIVX = DIV/IDIV
DRD = 3
EAR = P*EFR
EB = EAR-EUR

EDAR = (1/ESRC)*(REAR-ERRDM)
EED = ESRC*(SER+SSR)

EEP = EPRC*(GNPGR+RPGR)
EEV = PVV/PVDD
EFR = 2
EGAR = EAR-ERRPM
ENPGR = MAX(0,REGAR)

EPPGR = PPGRP+PPGRS
EPRC = 1
ERPGR = MIN(IRPGR,EPPGR)
ERRDM = DIV*DIVMC
ERRPM = P*PMC
ESRC = 1

EUR = EED+EEP+EEV+ERRDM+ERRPM
EVAR = ESRC*(EDAR-SSR-SER)
GNPGR = MIN(INPGR,ENPGR)
GPDR = NC*NCRRS*NCPRC
GPGR = GNPGR+RPGR

ID = ON/ONDRC
INGAD = 6
ISEAD = 60
NAD = 3
NCPRC = 14.71

NCRD = 6
NNPGR = MAX(0,RNAR)
NNPPR = PPEF*GNPGR
NPDR = P/PDD
NPGR = MIN(NNPGR,NNPPR)

NPPR = P*PPM
NPRC = 0.03
NRPGR = N/(NPRC*NAD)
NSER = (1/SED)*(IDIV-DIV)
ON = ON1+ON2+ON3

ONDRC = 0.5
PAX = P/(PNCRC*NC)
PDD = 6
PDRSD = 12
PMC = 0.1

PNCRC = 147.1
PONBA = NPDR*NPRC
PPGRP = EGAR/EPRC
PPGRS = PVV/(EPRC*PVDD)
PSER = MAX(0,REDAR)

PSSR = MAX(0,EDAR)
PVDD = 12
REAR = (EPRC)*(PPGRP-GNPGR-RPGR)
REDAR = PSSR-ISSR

REGAR = EPPGR-IRPGR
RESP = GPGR-NNPPR
RNAR = NRPGR-ERPGR
RPGR = MIN(NRPGR,ERPGR)
SAX = P/SCC

SCCAD = 60
SED = 12
SER = MIN(ISER,PSER)
SMR = SMRN*SMRM
SMRN = .01
SSD = 60
SSR = MIN(PSSR,ISSR)

IDIV = GRAPH(BS)
(0.00, 0.00), (10.0, 46.0), (20.0, 76.0), (30.0, 104), (40.0, 128), (50.0, 148), (60.0, 164), (70.0, 176), (80.0, 188), (90.0, 196), (100, 200)

ISCC = GRAPH(DIV)
(0.00, 20.0), (10.0, 23.0), (20.0, 32.0), (30.0, 57.0), (40.0, 94.0), (50.0, 102), (60.0, 112), (70.0, 116), (80.0, 118), (90.0, 119), (100, 120)

NCMR = GRAPH(PAX)
(0.00, 1.00), (0.2, 0.21), (0.4, 0.16), (0.6, 0.12), (0.8, 0.098), (1, 0.083), (1.20, 0.074), (1.40, 0.068), (1.60, 0.064), (1.80, 0.062), (2.00, 0.06)

NCRR = GRAPH(PAX)
(0.00, 0.00), (0.2, 0.01), (0.4, 0.02), (0.6, 0.04), (0.8, 0.06), (1, 0.083), (1.20, 0.096), (1.40, 0.106), (1.60, 0.114), (1.80, 0.118), (2.00, 0.12)

PPEF = GRAPH(DIVX)
(0.00, 0.5), (0.1, 0.49), (0.2, 0.46), (0.3, 0.43), (0.4, 0.39), (0.5, 0.35), (0.6, 0.25), (0.7, 0.18), (0.8, 0.13), (0.9, 0.11), (1, 0.1)

PPM = GRAPH(SAX)
(0.00, 1.00), (0.1, 0.96), (0.2, 0.88), (0.3, 0.7), (0.4, 0.5), (0.5, 0.34), (0.6, 0.2), (0.7, 0.1), (0.8, 0.04), (0.9, 0.01), (1, 0.00)

SCCT = GRAPH(DIV)
(0.00, 20.0), (10.0, 23.0), (20.0, 32.0), (30.0, 57.0), (40.0, 94.0), (50.0, 102), (60.0, 112), (70.0, 116), (80.0, 118), (90.0, 119), (100, 120)

SMRM = GRAPH(SAX)
(0.00, 1.00), (0.1, 0.96), (0.2, 0.88), (0.3, 0.7), (0.4, 0.5), (0.5, 0.34), (0.6, 0.2), (0.7, 0.1), (0.8, 0.04), (0.9, 0.01), (1, 0.00)

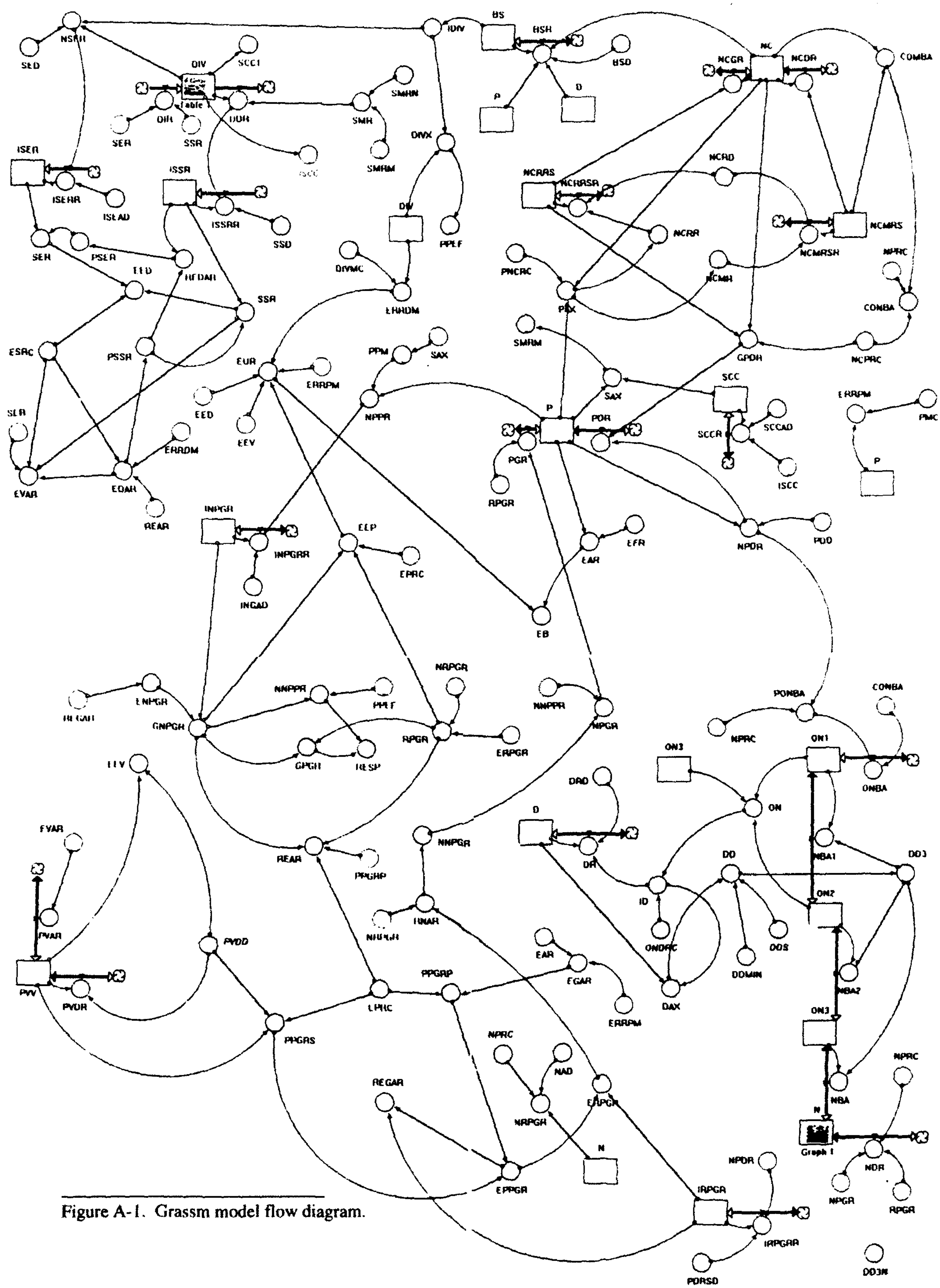


Figure A-1. Grassm model flow diagram.

Appendix B: Wetland Ecosystem Succession Model

This Appendix contains the diagram and the computer code of the constructed wetland ecosystem model

```
BS(t) = BS(t - dt) + (BSR) * dt
INIT BS = P+D+NC
BSR = (1/BSD)*(P+NC+D-BS)

D(t) = D(t - dt) + (DR) * dt
INIT D = (ON1+ON2+ON3)/ONDRC
DR = (1/DRD)*(ID-D)

DIV(t) = DIV(t - dt) + (DIR - DDR) * dt
INIT DIV = 1
DIR = (SER+SSR)
DDR = DIV*SMR

INPGR(t) = INPGR(t - dt) + (INPGRR) * dt
INIT INPGR = 0
INPGRR = (1/INGAD)*(NPPR-INPGR)

IRPGR(t) = IRPGR(t - dt) + (IRPGRR) * dt
INIT IRPGR = P/PDD
IRPGRR = (1/PDRSD)*(NPDR-IRPGR)

ISER(t) = ISER(t - dt) + (ISERR) * dt
INIT ISER = 0
ISERR = (1/ISEAD)*(NSER ISER)

ISSR(t) = ISSR(t - dt) + (ISSRR) * dt
INIT ISSR = DIV/SMRN
ISSRR = (1/SSD)*(DDR-ISSR)*HSM

N(t) = N(t - dt) + (NBA + NI - NDR - NE) * dt
INIT N = 40
NBA = ON3/DD3

NI = GRAPH(AFR )
(0.00, 0.00), (2.00, 0.392), (4.00, 0.784), (6.00, 1.18), (8.00, 1.57), (10.0, 1.96), (12.0, 2.35), (14.0, 2.74),
(16.0, 3.14), (18.0, 3.53), (20.0, 3.92)

NDR = NPRC*(NPGR+RPGR)

NE = GRAPH(AFR)
(0.00, 0.00), (2.00, 0.314), (4.00, 0.627), (6.00, 0.944), (8.00, 1.26), (10.0, 1.57), (12.0, 1.88), (14.0, 2.19),
(16.0, 2.51), (18.0, 2.82), (20.0, 3.14)

NC(t) = NC(t - dt) + (NCGR - NCDR) * dt
INIT NC = 0.548
```

```
NCGR = NC*NCRRS
NCDR = NC*NCMRS
NCMRS(t) = NCMRS(t - dt) + (NCMRSR) * dt
INIT NCMRS = .074
NCMRSR = (1/NCRD)*(NCMR-NCMRS)

NCRRS(t) = NCRRS(t - dt) + (NCRRSR) * dt
INIT NCRRS = 0.096
NCRRSR = (1/NCRD)*(NCRR-NCRRS)

ON1(t) = ON1(t - dt) + (ONBA - NBA1) * dt
INIT ON1 = (P*DD3N*NPRC)/PDD
ONBA = CONBA+PONBA
NBA1 = ON1/DD3

ON2(t) = ON2(t - dt) + (NBA1 - NBA2) * dt
INIT ON2 = ON1
NBA1 = ON1/DD3
NBA2 = ON2/DD3

ON3(t) = ON3(t - dt) + (NBA2 - NBA) * dt
INIT ON3 = ON2
NBA2 = ON2/DD3
NBA = ON3/DD3

P(t) = P(t - dt) + (PGR - PDR) * dt
INIT P = 12.5
PGR = NPGR+RPGR
PDR = NPDR+GPDR

PVV(t) = PVV(t - dt) + (PVAR - PVDR) * dt
INIT PVV = 0
PVAR = MAX(0,EVAR)
PVDR = PVV/PVDD

SCC(t) = SCC(t - dt) + (SCCR) * dt
INIT SCC = SCCT

SCCR = (1/SCCAD)*(ISCC-SCC)
AFR = 5
BSD = 12
COMBA = NC*NCMRS
CONBA = COMBA*NCPRC*NPRC

DAX = ID/D
DD = (DDMIN+(DDS*DAX))*DDWL
DD3 = DD/3
DD3N = 26
DDMIN = 13

DDS = 13
DIVMC = 0.05
DIVX = DIV/IDIVH
```

DRD = 3
EAR = P*EFR

EB = EAR-EUR
EDAR = (1/ESRC)*(REAR-ERRDM)
EED = ESRC*(SER+SSR)
EEP = EPRC*(GNPGR+RPGR)
EEV = PVV/PVDD
EFR = 2
EGAR = EAR-ERRPM
ENPGR = MAX(0,REGAR)

EPPGR = PPGRP+PPGRS
EPRC = 0.24
ERPGR = MIN(IRPGR,EPPGR)
ERRDM = DIV*DIVMC
ERRPM = P*PMC

ESRC = 1
EUR = EED+EEP+EEV+ERRDM+ERRPM
EVAR = ESRC*(EDAR-SSR-SER)
GNPGR = MIN(INPGR,ENPGR)
GPDR = NC*NCRRS*NCPRC

GPGR = GNPGR+RPGR
ID = ON/ONDRC
IDIVH = IDIV*HSM
INGAD = 5
ISEAD = 30

NCPRC = 1.98
NCRD = 6
NNPGR = MAX(0,RNAR)
NNPPR = PPEF*GNPGR
NPDR = P/PDD

NPGR = MIN(NNPGR,NNPPR)
NPPR = P*PPM
NPRC = .0155
NRPGR = (N/(NPRC*NAD))
NSER = (1/SED)*(IDIVH-DIV)

ON = ON1+ON2+ON3
ONDRC = 0.218
PAX = P/(PNCRC*NC)
PDD = 6
PDRSD = 12

PMC = 0.49
PNCRC = 19.84
PONBA = NPDR*NPRC
PPGRP = EGAR/EPRC
PPGRS = PVV/(EPRC*PVDD)

PSER = MAX(0,REDAR)
PSSR = MAX(0,EDAR)
PVDD = 12
REAR = (EPRC)*(PPGRP-GNPGR-RPGR)

REDAR = PSSR-ISSR
REGAR = EPPGR-IRPGR
RESP = GPGR-NNPPR
RNAR = NRPGR-ERPGR

RPGR = MIN(NRPGR,ERPGR)
SAX = P/SCC
SCCAD = 12
SED = 6
SER = MIN(ISER,PSER)

SMR = SMRN*SMRM
SMRN = .01*SMWL
SSD = 30
SSR = MIN(PSSR,ISSR)
WL = 1.5

DDWL = GRAPH(WL)
(0.00, 0.8), (0.188, 0.8), (0.375, 0.8), (0.563, 0.8), (0.75, 0.8), (0.938, 0.8), (1.13, 0.84), (1.31, 0.905), (1.50, 0.955), (1.69, 0.98), (1.88, 1.00), (2.06, 1.00), (2.25, 1.00), (2.44, 1.00), (2.63, 1.00), (2.81, 1.00), (3.00, 1.00), (3.19, 1.00), (3.38, 1.00), (3.56, 1.00), (3.75, 1.00), (3.94, 1.00), (4.13, 1.00), (4.31, 1.00), (4.50, 1.00)

HSM = GRAPH(AFR)
(0.00, 0.23), (2.86, 0.23), (5.71, 0.28), (8.57, 0.35), (11.4, 0.52), (14.3, 0.55), (17.1, 0.71), (20.0, 1.00)

IDIV = GRAPH(BS)
(0.00, 0.00), (125, 22.0), (250, 38.0), (375, 51.0), (500, 63.0), (625, 74.0), (750, 83.0), (875, 90.0), (1000, 93.0), (1125, 97.0), (1250, 100)

ISCC = GRAPH(DIV)
(0.00, 125), (20.0, 262), (40.0, 643), (60.0, 962), (80.0, 1087), (100, 1156), (120, 1206), (140, 1231), (160, 1237), (180, 1243), (200, 1250)

NAD = GRAPH(WL)
(0.00, 8.00), (0.5, 3.15), (1.00, 3.04), (1.50, 3.00), (2.00, 3.04), (2.50, 3.15), (3.00, 3.38), (3.50, 3.75), (4.00, 4.36), (4.50, 8.00)

NCMR = GRAPH(PAX)
(0.00, 1.00), (0.2, 0.21), (0.4, 0.16), (0.6, 0.12), (0.8, 0.098), (1, 0.083), (1.20, 0.074), (1.40, 0.068), (1.60, 0.064), (1.80, 0.062), (2.00, 0.06)

NCRR = GRAPH(PAX)
(0.00, 0.00), (0.2, 0.01), (0.4, 0.02), (0.6, 0.04), (0.8, 0.06), (1, 0.083), (1.20, 0.096), (1.40, 0.106), (1.60, 0.114), (1.80, 0.118), (2.00, 0.12)

PPEF = GRAPH(DIVX)

(0.00, 0.5), (0.1, 0.5), (0.2, 0.49), (0.3, 0.48), (0.4, 0.47), (0.5, 0.46), (0.6, 0.44), (0.7, 0.38), (0.8, 0.3), (0.9, 0.18), (1, 0.1)

PPM = GRAPH(SAX)
(0.00, 1.00), (0.1, 0.99), (0.2, 0.95), (0.3, 0.87), (0.4, 0.71), (0.5, 0.52), (0.6, 0.34), (0.7, 0.2), (0.8, 0.11), (0.9, 0.05), (1, 0.00)

SCCT = GRAPH(DIV)
(0.00, 125), (20.0, 262), (40.0, 643), (60.0, 962), (80.0, 1087), (100, 1156), (120, 1206), (140, 1231), (160, 1237), (180, 1243), (200, 1250)

SMRM = GRAPH(SAX)
(0.00, 1.00), (0.1, 0.99), (0.2, 0.95), (0.3, 0.87), (0.4, 0.71), (0.5, 0.52), (0.6, 0.34), (0.7, 0.2), (0.8, 0.11), (0.9, 0.05), (1, 0.00)

SMWL = GRAPH(WL)
(0.00, 1.10), (0.25, 1.10), (0.5, 1.10), (0.75, 1.10), (1.00, 1.09), (1.25, 1.02), (1.50, 1.00), (1.75, 1.02), (2.00, 1.09), (2.25, 1.10), (2.50, 1.10), (2.75, 1.10), (3.00, 1.10), (3.25, 1.10), (3.50, 1.10), (3.75, 1.10), (4.00, 1.10), (4.25, 1.50), (4.50, 1.50)

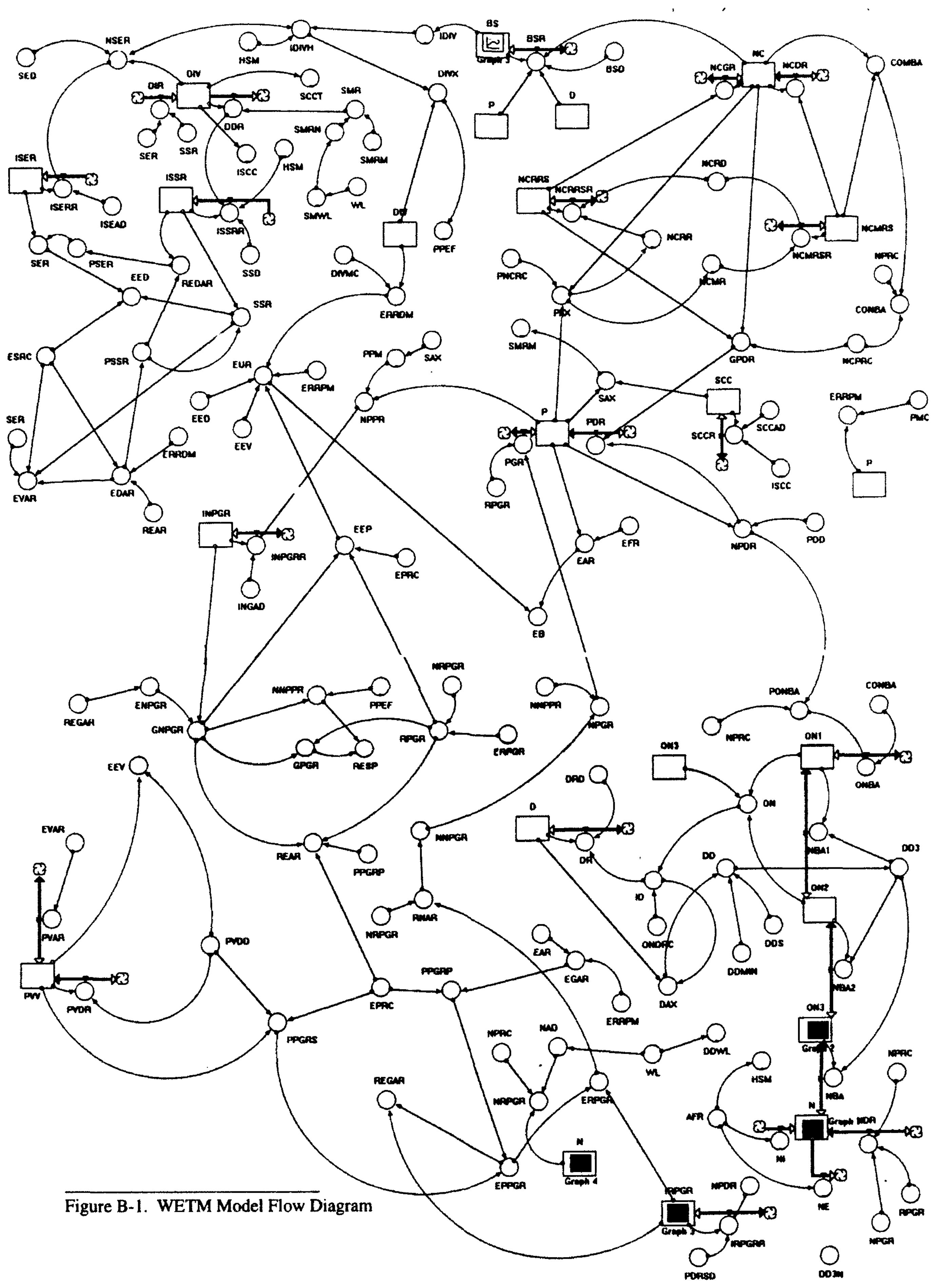


Figure B-1. WETM Model Flow Diagram

Appendix C: Calculations

1. Calculation used to find the Plant Maintenance Coefficient.
According to Mitsch, a fully mature wetland producing approximately 2500 g m^{-2} yr^{-1} net primary production requires approximately 10,000 kcal m^{-2} yr^{-1}. The WETM system is built to simulate a net primary production rate of 1250 g m^{-2} yr^{-1}. This leds to the following:

$$\frac{2500}{10000} = \frac{1250}{X}$$

where X = 5000 kcal m^{-2} yr^{-1}. 5000 represents a 35% increase from the low end of table 4-3. Using this percentage on the gross production quantities yeilds a vale of 12375 kcal m^{-2} yr^{-1} for WETM. Therefor the energy for plant maintenance is 7375 kcal m^{-2} yr^{-1}. To get the plant maintenance coefficient, the energy requirement is divided by the standing stock of the mature system as follows:

$$\frac{7375 \text{ kcal m}^{-2}\text{ yr}^{-1}}{1250 \text{ g m}^{-2}} \text{ X } \frac{1 \text{ yr}}{12 \text{ months}} = 0.49 \text{ cal g}^{-1}\text{mon}^{-1}$$

Therefor, PMC = 0.49 cal g^{-1} mon^{-1}

2. Conversion of kilo joules to calories.

To understand this conversion, an assumption must be made with respect to Gutierrez and Fey's representation of the unit calorie. Throughout their model they continually use the lower case symbol for calorie, cal. It is suggested that they simply lowered the case of this unit from Cal to cal. Kleiber details many calculations on fixation of energy of the sun by different types of crops. At no time did he calculate a value lower than an 1800 cal/g fixation requirement (19:340). This leads one to believe the reference to cal/g in GRASSM actually should have been Cal/g. This leads to the conversion factors of 1 Cal = 1 kcal = 1000 cal (18:20). Using this theory, it is assumed that each reference to cal in GRASSM actually should be Cal.

This leads to a conversion of kJ to cal as follows:

$$\frac{15\text{kJ x } 1000\text{J/kJ}}{4.184 \text{ J/cal}} = 3585 \text{ cal}$$

e-t/T

therefor the energy to plant requirement coefficient is:

$$\frac{3585\text{cal m-2 yr-1}}{1250 \text{ g m-2}} \text{ x } \frac{1\text{yr}}{12 \text{ month}} = 0.24 \text{ cal/g}$$

Hence, EPRC = 0.24 cal/g.

3. Calculation of time constant T for exponential decay of organic nutrients.

The half life values of several species of leaf biomass is averaged at 1.51 years. This allows use of the equation

$$0.5 = 1 - e^{-t/T}$$

where t is the actual time in years and T is the time constant. Since the data presented represent the time in years of the half life of decay, the value of t isequal to 1.51 years. Using this and solving for T, we get a time constant of 2.18 years or approximately 26 months. Hence the value of the decomposition delay normal is 26 months.

4. Calculation of species to hydrology multiplier, HSM.

Gosselink and Turner present data that shows differing species diversity with respect to water flow through the system. Their data ins't quantified in terms of flow rates, ratherit is expressed in flow characteristics. Basically, the information is broken down in the following table:

Species Present	Flow Characteristics
71	Good surface flow
51	Not adapted to strong water flow
39	slightly less flow through
37	Sheet flow
25	Gentle water flow
20	Isolated, little standing water
17	Wet, soggy

using this data and arbitrarily assigning 20 m^3/month as a good flow rate,and a poor flow rate at 2m^3/month, 71 species represent an optimum condition and is valued at 1.0. Therefore, at 20 m^3/month flow rate, the optimum number of species will be allowed to get established while at 2 m^3/month only 24% of that optimum will develop. This figure is derived by taking the percentage of low species to high species, or

17 at 2m^3/month divided by 71 at 20 m^3/month.

Actual schedual of test cases for model simulations:

TEST	Water Level	Nutrients	AVG FLOW RATE
1	1.5 meters	High	0 m/yr
2	1.5 meters	High	5 m/yr
3	1.5 meters	High	10 m/yr
4	1.5 meters	High	15 m/yr
5	1.5 meters	High	20 m/yr
6a	1.5 meters	High	5 + step(15,24) + step(-15,48) . . . + step(-15,720)
6b	1.5 meters	High	20 + step(-15,24) + step(15,48) . . . + step(15,720)
6c	1.5 meters	High	10 + step(-10,24) + S(5,48) + S(15,72) + S(-10,96) + S(5,120) + S(5,144) + S(-15,168) + S(15,192) + S(-10,216)
7a	1.5 meters	Low	5 m/yr
7b	1.5 meters	Low	10 m/yr
7c	1.5 meters	Low	20 m/yr
8a	Step (2.5,10)	High	20 m/yr
8b	Step (-1.5,10)	High	5 m/yr
9	1.5 meters	High, pulsed	10 m/yr
10a	1.5 meters	High, NPRC = 0.03	20 m/yr
10b	1.5 meters	High, NPRC = 0.0155	20 m/yr

Table 5-1. Test constraints run on WETM variables.

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Vita

Captain Robert A. Pompilio was born on 12 August 1960 in Pasaic, New Jersey. In 1978, he graduated from South Plainfield High School in South Plainfield, New Jersey. In 1983, he graduated from the University of Evansville, Evansville, Indiana, where he received a Bachelor of Science Degree in Civil Engineering. He was commissioned as a second lieutenant in the Air Force in September of 1983. From Oct 1983 to Dec 1986, he was assigned to Scott AFB, Il., as an Environmental Engineer/Community Planner. His duties ranged from developing the Air Installation Compatibility Use Zones to the design of environmental facilities. From Jan 1987 to Dec 1988, he was assigned to Dover AFB, De., where he served as the Readiness officer. From Jan 1989 to Feb 1990 he was assigned to Galena Air Station, Ak., as the Base Civil Engineer. He commanded a squadron of 95 individuals and his duties included base maintenance and operations, engineering, fire marshall, and environmental coordinator. From Feb 1990 to May 1993 he was assigned to Wright Patterson AFB, Oh., as the Chief of SABER. His duties included the development, procurement and management of a 15 million design and construction program. Currently he is attending the Air Force Institute of Technology as a graduate student in the Engineering and Management Program.

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SIMULATION OF HYDROLOGICAL INFLUENCES ON WETLAND ECOSYSTEM SUCCESSION

6. AUTHOR(S)

Robert A. Pompilio, Captain, USAF

7. PERFORMING

Air Force Institute of Technology, WPAFB OH. 45433-6583

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This research focuses on the development of a simulation model to determine the affects of hydrological influences on a wetland ecosystem. The model allows perturbations to the inputs of various wetland data which in turn, influences the successional development of the ecosystem.

This research consisted of converting a grassland ecosystem model to one which simulates wetland conditions. The critical factor in determining the success of wetland creation is the hydrology of the system. There are four of the areas of the original model which are affected by the hydrology .

The model measures the health or success of the ecosystem through the measurement of the systems gross plant production, the respiration and the net primary production of biomass. Altering the auxiliary variables of water level and the rate of flow through the system explicitly details the affects hydrologic influences on those production rates. Ten case tests depicting exogenous perturbations of the hydrology were run to identify these affects. Although the tests dealt with the fluctuation of water through the system, any one of the auxiliary variables in the model could be changed to reflect site specific data.

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